Dosimetry and uncertainty approaches for the million person study of low-dose radiation health effects: overview of the recommendations in NCRP Report No. 178

Article *in* International Journal of Radiation Biology · November 2018

DOI: 10.1080/09553002.2018.1536299

CITATIONS
20

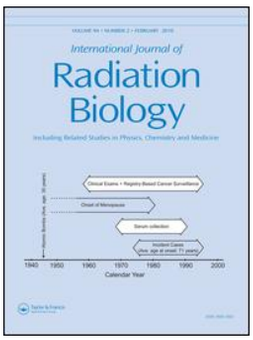
READS
536

19 authors, including:

Lawrence T Dauer
Memorial Sloan Kettering Cancer Center
162 PUBLICATIONS **3,193** CITATIONS
SEE PROFILE

André Bouville
National Institutes of Health
200 PUBLICATIONS **5,064** CITATIONS
SEE PROFILE

Harold L Beck
113 PUBLICATIONS **2,425** CITATIONS
SEE PROFILE



International Journal of Radiation Biology

ISSN: 0955-3002 (Print) 1362-3095 (Online) Journal homepage: http://www.tandfonline.com/loi/irab20

Dosimetry and uncertainty approaches for the million person study of low-dose radiation health effects: overview of the recommendations in NCRP Report No. 178

Lawrence T. Dauer, André Bouville, Richard E. Toohey, John D. Boice Jr., Harold L. Beck, Keith F. Eckerman, Derek Hagemeyer, Richard W. Leggett, Michael T. Mumma, Bruce Napier, Kathy H. Pryor, Marvin Rosenstein, David A. Schauer, Sami Sherbini, Daniel O. Stram, James L. Thompson, John E. Till, R. Craig Yoder & Cary Zeitlin

To cite this article: Lawrence T. Dauer, André Bouville, Richard E. Toohey, John D. Boice Jr., Harold L. Beck, Keith F. Eckerman, Derek Hagemeyer, Richard W. Leggett, Michael T. Mumma, Bruce Napier, Kathy H. Pryor, Marvin Rosenstein, David A. Schauer, Sami Sherbini, Daniel O. Stram, James L. Thompson, John E. Till, R. Craig Yoder & Cary Zeitlin (2018): Dosimetry and uncertainty approaches for the million person study of low-dose radiation health effects: overview of the recommendations in NCRP Report No. 178, International Journal of Radiation Biology, DOI: 10.1080/09553002.2018.1536299

To link to this article: https://doi.org/10.1080/09553002.2018.1536299

Published online: 19 Nov 2018.

INTERNATIONAL JOURNAL OF RADIATION BIOLOGY
https://doi.org/10.1080/09553002.2018.1536299

Taylor & Francis
Taylor & Francis Group

REVIEW

Dosimetry and uncertainty approaches for the million person study of low-dose radiation health effects: overview of the recommendations in NCRP Report No. 178

Lawrence T. Dauer[a], André Bouville[b], Richard E. Toohey[c], John D. Boice , Jr.[d,e], Harold L. Beck[f], Keith F. Eckerman[g], Derek Hagemeyer[h], Richard W. Leggett[g], Michael T. Mumma[i], Bruce Napier[j], Kathy H. Pryor[j], Marvin Rosenstein[k], David A. Schauer[l], Sami Sherbini[m], Daniel O. Stram[n], James L. Thompson[o], John E. Till[p], R. Craig Yoder[q] and Cary Zeitlin[r]

[a]Radiology and Medical Physics, Memorial Sloan Kettering Cancer Center, New York, NY, USA; [b]National Cancer Institute (retired), Bethesda, MD, USA; [c]M.H. Chew and Associates, Oak Ridge, TN, USA; [d]National Council on Radiation Protection and Measurements, Bethesda, MD, USA; [e]Vanderbilt Epidemiology Center, Division of Epidemiology, Department of Medicine, Vanderbilt-Ingram Cancer Center, Vanderbilt University Medical Center, Nashville, TN, USA; [f]U.S. Department of Energy (retired), New York, NY, USA; [g]Oak Ridge National Laboratory, Oak Ridge, TN, USA; [h]Oak Ridge Associated Universities, Oak Ridge, TN, USA; [i]International Epidemiology Institute, Rockville, MD, USA; [j]Pacific Northwest National Laboratory, Richland, WA, USA; [k]National Council on Radiation Protection and Measurements, Bethesda, USA; [l]International Commission on Radiation Units, Bethesda, MD, USA; [m]U.S. Nuclear Regulatory Commission, Washington, DC, USA; [n]University of Southern California, Los Angeles, CA, USA; [o]U.S. Nuclear Regulatory Commission, Arlington, TX, USA; [p]Risk Assessment Corporation, Neeses, SC, USA; [q]Landauer, Inc, Glenwood, IL, USA; [r]Leidos Innovations Corporation, Houston, TX, USA

ABSTRACT

Purpose: Scientific Committee 6–9 was established by the National Council on Radiation Protection and Measurements (NCRP), charged to provide guidance in the derivation of organ doses and their uncertainty, and produced a report, NCRP Report No. 178, Deriving Organ Doses and their Uncertainty for Epidemiologic Studies with a focus on the Million Person Study of Low-Dose Radiation Health Effects (MPS). This review summarizes the conclusions and recommendations of NCRP Report No. 178, with a concentration on and overview of the dosimetry and uncertainty approaches for the cohorts in the MPS, along with guidelines regarding the essential approaches used to estimate organ doses and their uncertainties (from external and internal sources) within the framework of an epidemiologic study.

Conclusions: The success of the MPS is tied to the validity of the dose reconstruction approaches to provide realistic estimates of organ-specific radiation absorbed doses that are as accurate and precise as possible and to properly evaluate their accompanying uncertainties. The dosimetry aspects for the MPS are challenging in that they address diverse exposure scenarios for diverse occupational groups being studied over a period of up to 70 y. Specific dosimetric reconstruction issues differ among the varied exposed populations that are considered: atomic veterans, U.S. Department of Energy workers exposed to both penetrating radiation and intakes of radionuclides, nuclear power plant workers, medical radiation workers, and industrial radiographers. While a major source of radiation exposure to the study population comes from external gamma- or x-ray sources, for some of the study groups, there is also a meaningful component of radionuclide intakes that requires internal radiation dosimetry assessments.

ARTICLE HISTORY
Received 7 September 2018
Revised 9 October 2018
Accepted 10 October 2018

KEYWORDS
NCRP; dosimetry; epidemiology; radiation

Introduction

The National Council on Radiation Protection and Measurements (NCRP) is coordinating an expansive epidemiologic effort entitled the One Million U.S. Workers and Veterans Study of Low- Dose Radiation Health Effects [One Million U.S. Workers and Veterans Study (MPS[1])] (Boice 2012a; Bouville et al. 2015; Boice et al. 2018). The primary aim of the MPS is to provide scientifically valid information and improve precision on the level of radiation risk when exposures are received gradually over time, and not acutely as was the case for Japanese atomic-bomb survivors. The major health outcome of interest for the MPS is cancer mortality, but other causes of death such as cardiovascular disease and cerebrovascular disease will be evaluated. The validity of the MPS is tied to the validity of the dose reconstruction approaches to provide accurate estimates of organ doses (i.e. the absorbed dose averaged over all parts of an organ or tissue) and their accompanying uncertainties. The focus is on providing the best estimate of organ dose and uncertainty for each individual, and to (when possible)

CONTACT Lawrence Dauer dauerl@mskcc.org Department of Medical Physics, Memorial Sloan Kettering Cancer Center, 1275 York Avenue, Box 84, New York, NY 10065, USA

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/irab.

characterize shared uncertainties that affect groups of individuals within the various cohorts considered.

NCRP established Scientific Committee 6-9 (SC 6-9) and tasked the committee members with developing a report to provide guidance in the derivation of organ doses and their associated uncertainty for epidemiologic studies in general, with a focus on the workers and atomic veterans that make up the MPS coordinated by NCRP (Boice 2012a, 2014a; Bouville et al. 2015). The study populations include atomic veterans[2], Department of Energy (DOE) workers, nuclear power plant (NPP) workers, medical radiation workers, and industrial radiographers. Organ doses from exposure to all the relevant external and internal sources for a given population are being derived. The Report covers the specifics of practical dose reconstruction for the epidemiologic studies included in the MPS with uncertainty analysis discussions and is a specific application of the previous guidance provided in NCRP Reports Nos. 158, 163, 164, and 171 (NCRP 2007, 2009b, 2009c, 2012). An interim status of the work of SC 6-9 was initially presented at the fiftieth annual meeting of the NCRP, 'NCRP: achievements of the past 50 years and addressing the needs of the future' (NCRP 2014), and a synopsis of that update was previously published (Bouville et al. 2015). The final NCRP Report No. 178 (NCRP 2018b) (the Report) was developed by multi-disciplinary experts based on a comprehensive review of available data, developing methods, and reviewed by the council.

This paper summarizes description of the cohorts in the MPS, several guidelines, and key points of the Report. Readers are encouraged to review the complete report for the discussion of specific background material, case studies, as well as cohort-specific considerations and recommendations. While the report was primarily aimed at providing guidance for the MPS, much of the material is applicable to any high-quality radiation epidemiologic study and should be considered for both future and ongoing research.

Overview of cohorts in the MPS

The MPS seeks to combine the radiation dose and mortality experiences from several occupational groups. The dosimetry aspects for the MPS are challenging in that they address diverse exposure scenarios for the various occupational groups being followed-up over a period of up to 70 y (Boice 2012a, 2012b, 2013a, 2013b, 2013c). These sub-cohorts have unique aspects with regard to exposure scenarios and organ dose and accompanying uncertainty estimation. The dosimetric issues differ among the exposed populations: atomic veterans, DOE workers, NPP workers, medical radiation workers, and industrial radiographers.

For the MPS, an attempt will be made to derive annual organ doses and their associated uncertainties for organs typically addressed in an epidemiological study, with particular emphasis on the most relevant organs for which cancer or other disease mortality data are available, especially for the radiosensitive sites [for example, active bone marrow, female breasts, thyroid (for young persons), lungs, heart, brain (dementia and associated conditions)]. To date, the derivation of annual organ doses and their associated uncertainties from the available recorded dose quantities and other information has been performed for part of the U.S. DOE workers, is well under way for the atomic veterans, has been undertaken for the NPP workers and the industrial radiographers, and is at the planning stage for the medical radiation workers. For most of the MPS cohorts, external sources were the predominant mode of exposure. However, preliminary estimates indicate that about half of the DOE workers also were exposed to internal irradiation from intakes of radionuclides.

For the MPS, all career occupational doses are sought. This requires linkages with the Radiation Exposure Information and Reporting System (REIRS), DOE Radiation Exposure Monitoring System (REMS) (DOE 2015), DOE historical databases, military databases, and the Landauer, Inc. (Landauer) database. These linkages are discussed in Boice et al. (2006a). One of the challenges for career dosimetry for early workers is that many of them, up to 25%, worked at facilities other than the index facility and dosimetry for these other facilities have to be accessed, interpreted, and then incorporated, often with lower quality assurances than for the prime facility.

It is recognized that the MPS and its approaches to dosimetry are a work in progress and there will be flexibility and changes in direction as new information is obtained, both with regard to dosimetry and with regard to the epidemiologic features of the study components.

U.S. Department of energy workers

Scores of facilities involved in the production of nuclear weapons, fuel rods, heat sources, or other devices containing large quantities of radioactive material have been operated in the USA since the 1940s. Workers at these facilities have the potential for elevated intake of radionuclides as well as exposure to external irradiation. Most of the populations that constitute the 290,000 DOE workers have been previously studied, but over 20 y ago. The populations recently under investigation include the workers at Rocketdyne (Leggett et al. 2005; Boice et al. 2006a, 2006b, 2011), Mound (Boice et al. 2014), and Mallinckrodt (Dupree-Ellis et al. 2000; Ellis et al. 2018; Golden et al. 2018). Populations that will soon be initiated for study include workers at Los Alamos (Wiggs et al. 1994), Rocky Flats (Gilbert et al. 1993), and Fernald (Silver et al. 2013) and those in the U.S. nuclear weapons complex who received annual occupational recorded doses of 50 mSv or more (Fry et al. 1996). Two case studies, Rocketdyne and Mound, are used in the NCRP Report No. 178 to illustrate the typical issues encountered in a dose reconstruction for radiation workers at a production facility and to describe the common sources of uncertainty in the reconstructed doses, which were mainly due to intakes of radionuclides. In addition, a detailed description of the issues of complex dose reconstruction at the Mallinckrodt Chemical Works, an early uranium processing facility, is presented in an appendix (Ellis et al. 2018).

The first case study (Boice et al. 2006a, 2006b, 2011) is a dose reconstruction for the 5801 workers who were monitored for radiation exposure and employed between 1948 and 1999 at the Rocketdyne (formerly Atomics International) Site near Los Angeles, California. Rocketdyne workers were involved in a wide range of radiological activities, including uranium and plutonium fuel fabrication, spent-fuel evaluation, radiochemistry, and storage of nuclear material. Workers were exposed to a number of radionuclides including isotopes of cerium, cesium, hydrogen (i.e. tritium), plutonium, promethium, strontium, thorium, and uranium.

The second case study (Boice et al. 2014) is a dose reconstruction for the 4977 workers at the Mound Site in Miamisburg, Ohio, who were monitored for radiation exposure and were first hired between 1944 and 1979. The Mound analysis was performed as part of a pilot study of the feasibility of conducting a time- and cost-efficient epidemiologic study of radiation workers at production facilities across the USA. The dose reconstruction for Mound generally followed the scheme laid out earlier for the Rocketdyne Site but differed in some ways from the Rocketdyne analysis, primarily due to differences in the dominant internal emitters at the two sites and in the main sources of uncertainty in organ dose estimates for the internal emitters.

Atomic veterans

The cohort of atomic veterans consists of military personnel included in the Eight Series Study (a cohort of 114,270 military personnel who participated in eight nuclear weapon test series) and were mainly exposed at either:

- the Nevada Test Site (NTS, currently named the Nevada National Security Site) where they participated in military maneuvers, observed nuclear weapons tests, or provided support during related operations that occurred from 1952 through 1957;
- the Pacific Proving Grounds where personnel were aboard ships or stationed on islands in the area during and following the nuclear weapons tests from 1946 through 1962; or
- the first nuclear weapons test, TRINITY, which took place in 1945 in New Mexico, where they participated in security, various test preparation activities, and post-shot monitoring.

Dose or dose-related information is available in the U.S. Department of Defense (DOD) Nuclear Test Personnel Review (NTPR) records for each veteran who participated in the Eight Series Study. The NTPR assembled a wealth of information from classified and unclassified historical records collected during the nuclear atmospheric tests and also records of military personnel that participated in the testing. However, the purpose of the NTPR Program was to estimate organ doses to be used for compensation and these organ doses were often deliberately high-sided in accordance with regulations NTPR was required to follow. The mean cumulative absorbed dose in the whole body calculated by NTPR for the 113,580 veterans included in the MPS is $<$10 mGy with 2% of these veterans receiving a cumulative whole-body dose $>$50 mGy.

Efforts have been undertaken to refine and modify as necessary the information available in the NTPR records to produce an organ dose estimate as unbiased as possible and suitable for epidemiology with a corresponding uncertainty estimate. Details about the dose assessment methods currently applied in the study of atomic veterans are reported in Beck et al. (2017) and Till et al. (2014). The initial focus of the atomic veterans study is on leukemia mortality. Thus, the organ of interest is active bone marrow. Because of cost and time, it was found impractical to conduct historical dose reconstructions on all of the 114,270 cohort members in the Eight Series Study. Therefore, organ doses are estimated for $\sim$2,000 individuals consisting of cases based on diagnosis of leukemia and male breast cancer and a 1% random sample of the entire cohort, used for comparison in a case-cohort design. Primary emphasis is given to external exposure since almost all the exposure to active bone marrow is known to be from penetrating external radiation. Future follow-up investigations will include other cancers such as bone, liver, salivary gland, and thyroid.

Nuclear power plant workers

About 600,000 workers have been employed in NPPs in the USA since the first commercial production of electricity in 1957. Because the average annual recorded dose of workers has decreased over the years down to $\sim$2 mSv on average, only the workers at NPPs first employed from 1957 through 1984 are considered in the MPS. About 330,000 cohort members were selected from databases available from the REIRS, which is maintained by the U.S. Nuclear Regulatory Commission (NRC 2011), and Landauer, Inc. (Landauer) which is a dosimetry service provider. Most radiation exposures were due to penetrating external gamma rays with only a few neutron exposures or internal contamination exposures. A 10% sample of workers with cumulative recorded dose $<$10 mSv (i.e. from personal monitors) was studied for purposes of cost efficiency and provided a strong low-dose category of over 20% of the studied population. The mean recorded cumulative dose for the remaining 145,209 workers is $\sim$50 mSv, with 25% of them receiving a cumulative recorded dose $>$50 mSv.

Medical workers

Medical radiation workers represent a large fraction of radiation-exposed workers, with $\sim$2.5 million monitored workers in 2006 (NCRP 2009a). Historically, the average annual occupational effective dose estimates have trended downward for the medical radiation worker populations (Linet et al. 2010). Most present day medical radiation workers generally experience very low radiation exposures, essentially from external irradiation. Those individuals who perform certain

fluoroscopically guided interventional procedures and potentially those who prepare or administer radionuclides for nuclear-medicine procedures are an exception to this generalization (Dauer 2014). Dosimetric information for 243,448 workers with cumulative recorded dose from personal monitors was obtained from Landauer. The mean cumulative recorded dose for these medical workers is ~100 mSv, with 36% of them receiving a cumulative recorded dose >50 mSv.

The derivation of organ doses from monitoring data poses difficult problems and reflects some of the sources of uncertainty for estimating organ doses for the medical worker cohort because of, among other factors:

- often extreme inhomogeneity of exposure over the body of personnel for any given procedure type;
- differing degrees and methods of radiation protection;
- inconsistent wearing of dosimeters by personnel (i.e. at times choosing not to wear dosimeters to avoid investigations) (NCRP 2010), combined with poor information, as well as high variability, on the workloads of physicians and technologists (i.e. the number of procedures of a given type conducted monthly or annually); and
- changing technology and medical procedure protocols.

Recognizing the need for more specific guidance on these challenges, NCRP recently chartered Scientific Committee 6-11 to provide dosimetry guidance for medical workers with a focus on lung dose reconstruction (Yoder et al. 2018). The approaches will rely on various exposure scenarios for medical workers classified as radiology, nuclear medicine, fluoroscopy-guided interventional, and radiation oncology.

Industrial radiographers

The sources of choice for industrial radiographic nondestructive testing are ^{192}Ir and ^{60}Co (NDT 2014). Industrial radiographers are only exposed via external irradiation, generally in an anterior-posterior (AP) geometry. To date, information on annual recorded dose has been collected by the MPS for 127,910 industrial radiographers. The main sources of information are the REIRS and the Landauer databases. The average cumulative recorded dose for these industrial radiographers is ~20 mSv (i.e. from personal monitors), with 10% of them receiving a cumulative recorded dose >50 mSv.

Supplemental populations of interest

In addition to the extensive discussion of the dose assessment of the populations that are part of the MPS, the NCRP Report No. 178 includes a description of supplemental population groups, which are of interest either because of uncommon conditions of exposure (astronauts), exemplary efforts to process and analyze dose records and information from the distant past (Mayak workers, Gilbert et al. 2004), or inclusion into exposure registries [U.S. Transuranium and Uranium Registries (USTUR, Tolmachev et al. 2011) and Radiation Emergency Assistance Center/Training Site (REAC/TS) accident registry].

Conclusions from NCRP Report No. 178

The Report provides guidelines regarding the estimation of organ doses for an epidemiologic study, estimation of organ doses from external irradiation, estimation of organ doses from internal irradiation, and assessment of uncertainties. In addition, several key points are made and discussed with regard to the overall dosimetry and uncertainty approaches.

Within the framework of an epidemiologic study evaluating the health effect attributed to a radiation dose, the quantity of interest is the annual absorbed dose to the organ or tissue (organ dose) that is assumed to be the origin of the radiation-induced cancer. For example, active bone-marrow dose is of interest if leukemia is the disease being considered in the epidemiologic study. Organ doses in most of the organs and tissues of the body can be calculated using relationships with measured or estimated personal dose equivalent [$H_p(10)$] values (in the case of external irradiation) or with unit of activity intakes of radionuclides (in the case of internal irradiation) that can be derived from ICRP publications. However, these relationships are not available for all organs and tissues of the body, so that a surrogate organ or tissue is sometimes used to estimate the organ dose to the organ or tissue that is assumed to be the origin of the radiation-induced cancer.

To facilitate time-dependent analyses that account for the accrual of radiation doses over time (Cox 1972; Preston et al. 2017), the organ dose is calculated on an annual basis. The annual organ dose that is considered is estimated for each year of the entire period of time over which the organ dose is delivered, beginning with the date of first exposure and ending with the date of last exposure, the date of cancer diagnosis or death (whichever is earlier). Although it is recognized that the absorbed dose distribution may not be uniform over all parts of the organ or tissue, it is assumed in the NCRP Report No. 178 that the absorbed dose averaged over all parts of the organ or tissue is the quantity of interest in the epidemiologic analysis.

Figure 1 provides a generic synopsis for presenting annual organ doses and their uncertainty for members of the populations included in the MPS. The synopsis is a summary of the exposure situation for each individual or group of individuals similarly exposed. The purpose is to display for that individual or group the characteristics of the exposure situation and either the results of a completed dose assessment or the elements of a dose assessment yet to be conducted. It addresses the total annual organ dose of interest (from all applicable external and internal radiation sources), with that total annual organ dose partitioned into low- and high-LET components (all expressed in Gy) without any weighting for the biological effectiveness of the type of radiation. For each partitioned component, the associated uncertainty is also addressed.

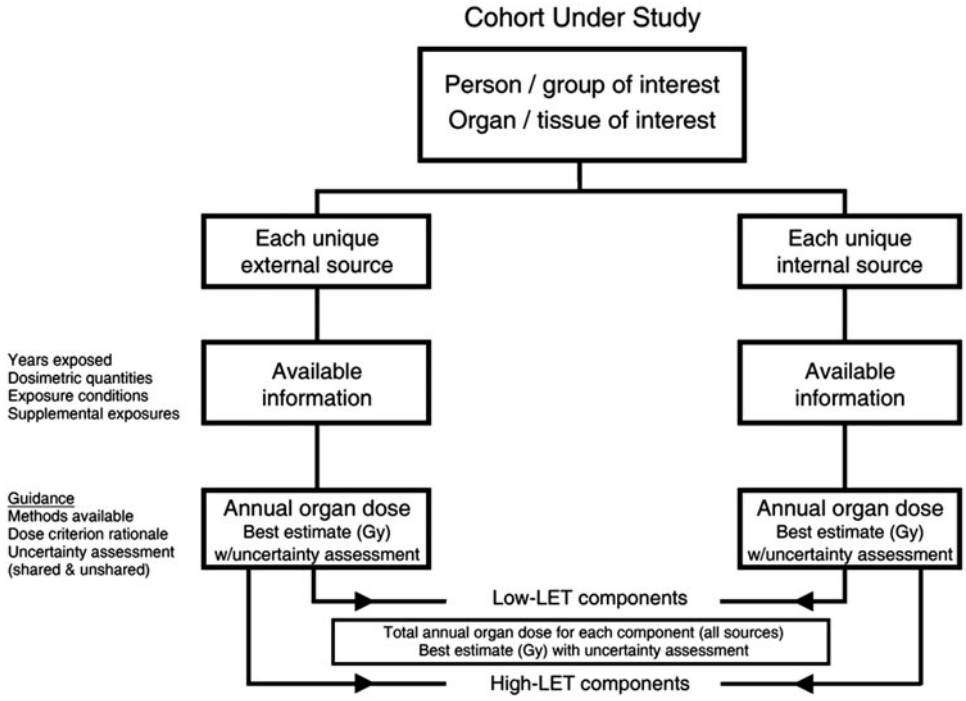


Figure 1. Generic synopsis for the presentation of annual organ dose and its uncertainty.

Estimation of organ doses from external irradiation

Most of the workers considered in the Report received radiation doses from external irradiation. Individual monitoring data, in terms of the quantities exposure or personal dose equivalent for strongly penetrating radiation in soft tissue at 10 mm [$H_p(10)$], are often available for these workers. The main effort then consists in defining the exposure scenarios for the various tasks carried out by the workers to determine the irradiation geometry and the energy spectrum of the incident photons on the body. The Report includes guidance on methodologies to estimate the dose coefficients relating the quantities exposure and $H_p(10)$ to organ dose, given the photon-energy spectrum and the irradiation geometry. It is important to note that the relative geometrical relationship between the dosimeter's placement on the worker, the incident source direction, and the organ or tissue is needed to estimate an organ dose.

Most records or personal dosimeter results reflect a single value of exposure or $H_p(10)$ for a monitoring period. The exposure scenario and pathways should assess the applicability of this single value as being appropriate for all areas of the body. Many exposure conditions result in different body areas being irradiated at much different levels as happens when protective aprons are worn during fluoroscopic procedures or when source shielding configurations cause large spatial variations in dose rate. Regulatory guidance requires personal monitoring devices to be worn at the location of highest dose; therefore, the recorded dosimeter results may overstate the $H_p(10)$ for some areas of the body. The derivation of organ doses from external irradiation assumes that an estimate exists of the quantity exposure or personal dose equivalent [$H_p(10)$]. For photons, the quantities assessed from personal monitoring dosimeters generally fall into two categories: early dosimeter data for which the quantity measured was exposure, generally measured at the surface of the body [expressed in roentgen (R)], and later data for which the quantity measured was $H_p(10)$, initially expressed in rem and now expressed in sievert (Sv). Therefore, early dosimeter data should be converted from exposure to $H_p(10)$.

For external exposures, the measured $H_p(10)$ or that value converted from a measurement of exposure provides an initial input to the derivation of the resultant organ doses of interest. Such derivations are aided by the results of computer models that have established relationships for the fundamental quantities of fluence and air kerma with both $H_p(10)$ and organ dose for various standard but idealized exposure conditions (Figure 2). Having a common relationship to fluence or air kerma, $H_p(10)$ and organ dose can be generally related to each other when the exposure conditions are comparable.

ICRP (1995) recommended conversion coefficients that relate air kerma (free-in-air) for monoenergetic photons to $H_p(10)$ for various photon energies and angles of incidence. These conversion coefficients have remained constant since their publication and continue to form the basis for dosimeter calibrations and performance testing in the USA. This stability is largely due to the unchanging specification of the slab phantom in which $H_p(10)$ is defined.

Factors that relate air kerma (free-in-air) or fluence to organ dose have changed over the years as improvements have been made in computer models, radiation transport equations, and the mathematical constructs used to represent the human body, particularly the size of the body and location of the internal organs. The most recent set of conversion coefficients for photons was published by ICRP (2010); that set is based on voxel phantoms of the human body using medical imaging data, a significant change from

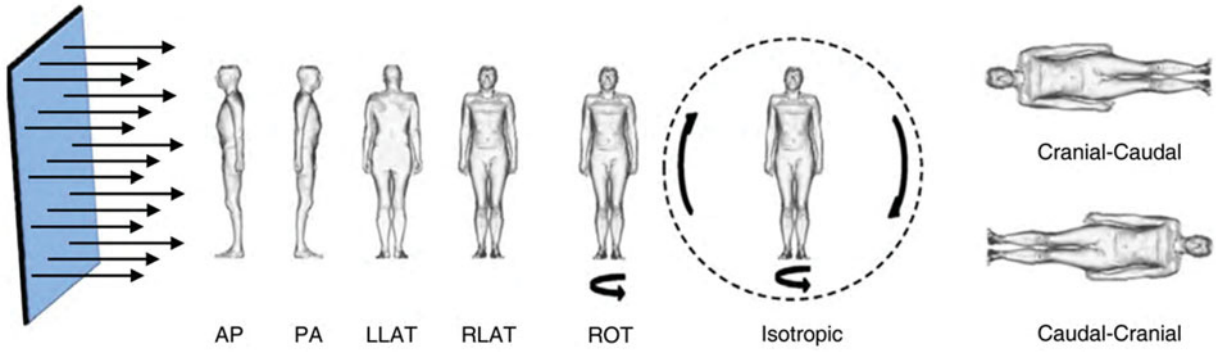


Figure 2. Schematic representation of the idealized geometries considered in NCRP Report No. 178 (2018), including: AP, PA, LLAT (left lateral), RLAT (right lateral), ROT (rotational), isotropic, cranial-caudal (top right) and caudal-cranial (bottom right) geometries.

the abstract body constructs used in past reports. These latest conversion coefficients relate air kerma and fluence to organ dose for 14 different organs in each of the male and female phantoms for various photon energies and exposure geometries.

The Report provides several dose coefficients [relating $H_p(10)$ and organ dose] that could be applicable to various external exposure scenarios and geometries for the MPS populations where personal dosimeter data were available. Figure 3 provides an example of dose coefficients for AP exposure geometry. The use of dose coefficients typically assumes uniform irradiation of the body from a designated angle of incidence, particularly for the torso where most of the radiosensitive organs reside. Some exposure scenarios and radiation environments do not result in relative uniform irradiation of the torso and head. In these situations, the estimate of $H_p(10)$ may need to be modified to reflect the nonuniform irradiation of different regions of the body. In the absence of detailed information on the irradiation geometry related to work activities, it is recommended to assume typical or representative geometries such as 100% AP or 50% AP plus 50% ROT (NCRP, 2009b), or 50% AP plus 50% isotropic (Thierry-Chef et al. 2007). In some facilities, multiple personal monitoring dosimeters may have been used by a single person during conditions of very nonuniform irradiation of the body. In such cases, the estimate of $H_p(10)$ from the dosimeter located nearest the organ of interest should be used. ANSI/HPS (2011) prescribes a procedure in which the body is divided into compartments for which a separate compartment-weighted $H_p(10)$ value is assessed from a dosimeter located nearest that compartment.

Other considerations are undetected dose (commonly referred to as missed dose) and unmonitored dose. Undetected dose is defined as the dose received that was not measured by the dosimeter, because it fell below the minimum detectable response of the dosimeter. Since the undetected dose may in reality range from zero to the minimum detectable, it is customary to assign some fraction of the minimum detectable dose (or some other clearly stated value) for each monitoring period in which the dosimeter reads zero (i.e. less than the minimum detectable). Unmonitored dose is that assumed to be received when a personal dosimeter was not worn, and often may be reconstructed from knowledge of workplace activities or from coworker data when others in the same location did wear dosimeters. This latter approach is typically applied to atomic veterans, when one or two dosimeters were issued to a unit that may have totaled 40 or more individuals.

Additional complications are:

- recorded doses may include a mixture of radiation types (e.g. photons and neutrons);
- organs or tissues may be only partially irradiated, for example when medical personnel wear lead aprons; and
- recorded doses from all facilities where the worker was exposed during a career are processed, with possible differences regarding the photon energy spectra, the irradiation geometries, and the measured dose quantities.

Estimation of organ doses from internal irradiation

In the case of occupational exposure from internal irradiation, the recorded dose, which is expressed in terms of committed effective dose or committed effective dose equivalent (CEDE), is not directly related to the dosimetric quantity of interest, which is the annual absorbed dose, averaged over all parts of the organ or tissue under consideration. Whenever possible, it is recommended to reconstruct the annual doses from internal irradiation on the basis of the available records of concentration of workplace air and surface contamination monitoring, and of individual bioassay data. The available information is processed to: estimate the radionuclide intake and its characteristics; and calculate the annual organ dose for each year of the entire period of time over which the organ dose is delivered, beginning with the date of first exposure and ending with the date of last exposure, the date of cancer diagnosis or death (whichever is earlier) (Boice et al. 2006a; Ellis et al. 2018).

Guidelines for estimating organ doses from internal emitters encountered in a large-scale production facility are described in detail in the Report. The Report notes that detailed dose reconstructions for internal emitters often require considerable time and effort for purposes of a given epidemiologic study and may not be justified below some level of intake of a given radionuclide. If comprehensive dose reconstructions for internal emitters would require prohibitive resources, it is useful to devise rapid screening techniques that yield conservative organ dose estimates based

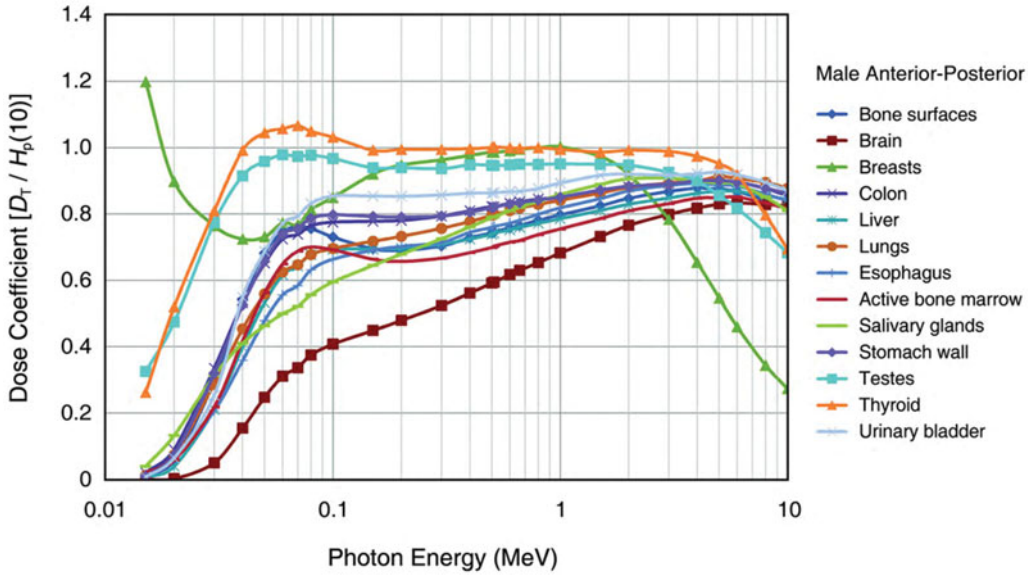


Figure 3. A plot of the relationship (dose coefficient) for an AP irradiation condition between the absorbed dose to the primary organs (DT)(mGy) in the male body and personal dose equivalent [H_p(10)] (mSv), for photons.

on available monitoring data. Dose reconstructions for internal emitters can then be limited to workers whose initial dose-related information is above a criterion level that represents insignificant organ doses for purposes of the epidemiologic study.

The same observation applies to organ doses that need to be reconstructed on the basis of environmental measurements for an external source, as is the case for some of the atomic veterans. Organ dose estimates for internal emitters should be radionuclide-specific (i.e. specific to each parent radionuclide taken into the body) and each parent radionuclide should be partitioned into organ dose from low-LET components and from high-LET components [all expressed in absorbed dose (in Gy)]. Organ dose estimates for external irradiation and for all addressed internal emitters should be summed to get the total annual organ doses (separately for the various low- and high-LET components) for individual workers or similar groups of workers.

Assessment of uncertainties

Estimates of organ dose obtained in a dose reconstruction have limitations and are uncertain. Limitations and lack of certainty in organ doses can result from factors such as:

- lack of complete knowledge of an exposure scenario;
- uncertainty in relevant measurements;
- lack of relevant data at locations and times of exposure;
- uncertainty in internal dosimetry; and
- conversion of externally measured quantities to organ doses.

All uncertainties, including uncertainties in exposure scenarios and uncertainties in data and models used to estimate organ dose, should be considered and taken into account in an appropriate manner in a dose reconstruction. As discussed in previous NCRP reports (NCRP 2007, 2009b, 2009c, 2012), the uncertainties can be classified as classical or Berkson, random or systematic, aleatory or epistemic, Type A or Type B, and shared or unshared. In the NCRP Report No. 178, the uncertainties are usually classified as shared or unshared. In the context of epidemiologic studies, knowledge of the existence and likely magnitude of correlations arising from shared parameters is essential to proper interpretation and use of the organ dose estimates (e.g. Stram and Kopecky 2003; Li et al. 2007; NCRP 2009c; Kwon et al. 2016). Depending on the relative importance of shared and unshared uncertainties, several approaches may be used to represent uncertainty in dosimetry numerically.

The first approach consists in attaching to each dose estimate an uncertainty estimate applicable to that specific person's dose. This approach may be used if almost all uncertainty is due to unshared uncertainty [due for example to imperfections in individual input data (e.g. location, shielding) that can be treated as independent from individual to individual]. This uncertainty estimate, which is based on an analysis of the uncertainties associated with each parameter used in the dose-estimation process, can be calculated either analytically or by means of a single Monte–Carlo procedure. It can also be an expert guess based on subjective judgment (NCRP 2009c).

In a second approach, which can be used if shared uncertainty is expected to be significant, a single uncertainty estimate can be applied to all subjects in a portion of a cohort affected by the same source of uncertainty, resulting in a covariance matrix of dose uncertainties. The idea of using both organ dose estimates for the study participants and a covariance matrix (representing both shared and unshared uncertainty) was described, for example, by Stram et al. (2015).

A third approach to representing uncertainty for complex exposure situations in which the shared uncertainty is expected to be significant has been to represent the shared/unshared uncertainties as repeated draws from a two-dimensional Monte–Carlo procedure that provides many as opposed to just

one estimate of organ dose for each subject (e.g. Simon et al. 2015).

At the onset of the epidemiologic study, it is highly recommended for the dosimetrists to work closely with the statisticians/epidemiologists to decide how to characterize and present the uncertainties in the dose estimates.

Key points of NCRP Report No. 178

Several key points are made and discussed in the Report as general guidance and for assessment of organ doses from external and internal sources, as well as evaluation of uncertainties.

General guidance:

- The goal of the dosimetry is to estimate annual absorbed doses to the organ or tissue (annual organ dose) that is assumed to be the origin of the radiation-induced cancer of interest.
- When performing dose reconstructions for estimating annual organ doses, it is important to recognize that each sub-cohort may require a different methodology.
- Although each radiation sub-cohort is unique, common principles for dose assessment will facilitate the combination of sub-cohorts in the MPS.
- Where possible, annual organ doses obtained at other facilities where the individual may have worked are important to consider.
- Applying a decision level below which detailed dose reconstruction need not to be done is appropriate and can result in a considerable reduction in dosimetry effort without affecting the epidemiologic results.
- The coordination and close interaction of the dosimetric and epidemiologic teams is critical to the success of an epidemiologic study.

Assessment of organ doses from external sources:

- The basic procedure for estimating organ doses from external irradiation is similar for all the sub-cohorts and starts with using personal or environmental measurement data that can be applied to a scenario of exposure.
- The process of deriving organ doses from dosimeter results is relatively straightforward for photons. For many of the sub-cohorts in the MPS, the sensitivity of the derivations is not very dependent on the photon energies and on the geometry of irradiation. However, exceptions are found in those sub-cohorts exposed to low photon energies, when the organ of interest is small and asymmetrically located in the body. In this case, the geometry of irradiation causes large spatial differences across the body.

Assessment of organ doses from internal sources:

- Although the major source of radiation exposure for many sub-cohorts of the MPS comes from external penetrating radiation, some sub-cohorts may have a meaningful component of radionuclide intakes that requires addressing specific assessment techniques. However, detailed dose reconstructions for such intakes may not be justified (based on considerable time and effort) below some screening level of intake of a given radionuclide.
- Organ doses from internal sources can be estimated using available records on concentration of radionuclides in air or on surfaces, from bioassays or other biological techniques and combined with organ doses from external sources for epidemiologic studies of cancer risk.

Evaluation of uncertainties:

- All organ dose estimates obtained in a dose reconstruction have limitations and uncertainties that should be identified, considered, and taken into account in an appropriate manner in a dose reconstruction.

Notes

1. The MPS has had a number of name changes over the years. The most recent is the Million Person Study of Low-Dose Radiation Health Effects (MPS). Both Million Worker Study (MWS) and MPS refer to the same program of studies.
2. Atomic veterans are military personnel who participated in the nuclear weapons testing program.

Disclosure statement

The authors declare no personal conflicts of interest. The views expressed in this paper represent collective opinions of the authors and are not necessarily those of their professional affiliations.

Funding

This work was supported in part by grants from the U.S. Department of Energy [grant numbers: DE-AU0000042 and DE-SC0008944] awarded to the National Council on Radiation Protection and Measurements, which included interagency support from the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, and the National Aeronautics and Space Administration; a grant from the U.S. Nuclear Regulatory Commission [grant number: NRC-HQ-60-14-G-0011], grants from the Centers for Disease Control and Prevention [grant numbers: 5UE1EH000989 and 5NUE1EH001315], and grants from the National Aeronautics and Space Administration [grant numbers: NNX15AU88G and 80NSSC17M0016]. We acknowledge the support provided by the U.S. Department of Defense/Defense Threat Reduction Agency and the U.S. Department of Veterans Affairs. We acknowledge the leadership by the Chair of SC 6-9 Andre Bouville, the major support of the NCRP Secretariat, including, Managing Editor Cindy L. O'Brien, Office Manager Laura J. Atwell, and Executive Directors James Cassata (2012–2014), David Smith (2014–2016), and Kathy Held (2016–2018). We express our gratitude to the Council members for the time and effort devoted to the review of NCRP Report No. 178.

Notes on contributors

Lawrence T. Dauer, PhD, is Associate Attending Physicist specializing in radiation protection at Memorial Sloan Kettering Cancer Center in the Departments of Medical Physics and Radiology. He is a Council and Board member of the NCRP and served as a member of the ICRP Committee 3, Protection in Medicine.

André Bouville, PhD, is a leading expert on radiation dose reconstruction and led the Dosimetry Unit of the Radiation Epidemiology Branch at NCI until he retired at the end of 2010. He chaired NCRP SC 6-9 on the dosimetry for the Million Person Study, producing NCRP Report No. 178.

Richard E. Toohey, PhD is a physicist with over 45 years of experience in health physics, especially internal radiation dosimetry, dose reconstruction, and radiological emergency response. He recently retired from Oak Ridge Associated Universities, where he served as director of the Radiation Internal Dose Information Center and held other leadership roles.

John D. Boice, Jr., ScD is a radioepidemiologist with over 40 years of experience. He is the President of the National Council on Radiation Protection and Measurements and a Professor of Medicine at Vanderbilt University. Dr. Boice is the creator and leader of the Million Person Study in the United States.

Harold L. Beck, BS is a leading expert on radiation dose reconstruction with more than 50 years of experience in radiation dosimetry, radiation metrology, and dose reconstruction uncertainty. He served for over 36 years in various scientific and management positions in the Department of Energy Environmental Measurements Laboratory.

Keith F. Eckerman, PhD is a leading expert in computational and phantom dosimetry, served on ICRP Committee 2, and is an Emeritus Member of the ICRP. He has received several scientific achievement awards, including the 39th Lauriston Taylor Lecturer for the NCRP. He is currently a retired staff member of the Environmental Sciences Division of the ORNL.

Derek Hagemeyer, BS is the Associate Director for Human Health and Environment at ORAU. He serves as the principal investigator for the DOE Radiation Exposure Monitoring System and the US NRC Radiation Exposure Information and Reporting System projects. He is Vice Chairman of the international Information System on Occupational Exposure Working Group on Data Analysis.

Richard W. Leggett, PhD is a research scientist in the Environmental Sciences Division at Oak Ridge National Laboratory (ORNL). His main research is in physiological systems modeling, with primary applications to the biokinetics and dosimetry of radionuclides and radiation risk analysis. He is a member of ICRP Committee 2 and the Task Group on Internal Dosimetry.

Michael T. Mumma is the Director of Information Technology at the International Epidemiology Institute and the International Epidemiology Field Station for Vanderbilt University Medical Center. He has over 20 years of experience in data analysis and conducting epidemiologic investigations.

Bruce Napier, M.S. is a Staff Scientist in the Environmental Analysis and Engineering Group at PNNL. He is an expert in the areas of radiation dose reconstruction, computer modeling, environmental analysis, and human health risk analysis. Mr. Napier is a Scientific Vice President and past member of the Board of Directors of NCRP.

Kathy H. Pryor, M.S. is currently on the NCRP Board of Directors and is Scientific Vice President of Program Area Committee 2. Ms. Pryor was Chief Health Physicist PNNL with previously experience in nuclear power and universities. Ms. Pryor served as President of the HPS, Chair of the ABHP, and is President of the AAHP.

Marvin Rosenstein, Ph.D. is an NCRP consultant. He was Director, Office of Health Physics at the Center for Devices and Radiological Health, US FDA and previously served 33 y as a Commissioned Officer in the US PHS. He is a Distinguished Emeritus Member of NCRP and an Emeritus Member of ICRP Committee 3, Protection in Medicine.

David A. Schauer, Sc.D. is the Executive Secretary of the ICRU. He served as an officer in the U.S. Navy and on the faculty of the Radiology and Radiological Sciences Department at the Uniformed Services University of the Health Sciences. He previously served as NCRP Executive Director and is Executive Director Emeritus.

Sami Sherbini, Ph.D. is a senior level advisor for health physics at the US NRC, where he has held progressively more technical positions in providing expertise to support rulemaking in radiation protection, nuclear medicine, and other radioactive materials regulation. Prior to the NRC, he worked in the commercial nuclear industry, including Three Mile Island.

Daniel O. Stram, is Professor in the Department of Preventive Medicine at the Keck School of Medicine of the University of Southern California. He served as a postdoctoral fellow in the Biostatistics Department of the Harvard School of Public Health and was a research associate at the RERF in Hiroshima, Japan.

James L. Thompson, B.S. initially served as a nuclear propulsion plant operator in the U.S. Navy, then became a health physicist working as a radioactive materials inspector for the Texas Department of Health, Bureau of Radiation Control, and currently is a Senior Health Physicist with the US NRC.

John E. Till, Ph.D. is the founder and President of Risk Assessment Corporation with more than 40 years of experience in environmental dosimetry. He received the E.O Lawrence award in 1995 and delivered the L.S. Taylor lecture in 2013. He also served in the U.S. Navy Nuclear Submarine Program, retiring as a Rear Admiral in 1999.

R. Craig Yoder, Ph.D. directed Landauer's technical activities relating to radiation dosimetry, particularly for applications in radiation protection for over 30 years. An internationally known expert in radiation monitoring, he led the development of optically stimulated luminescence. He is a member of NCRP and former President of the Council on Ionizing Radiation Measurements and Standards.

Cary Zeitlin, Ph.D. is a Research Scientist at Leidos Innovations Corporation, working in the Space Radiation Analysis Group at the NASA Johnson Space Center, with their programs in space radiation physics and biology. He performs operations and data analysis for the Radiation Assessment Detectors aboard the Curiosity Mars rover and the International Space Station.

ORCID

John E. Till http://orcid.org/0000-0003-3666-8806

References

American National Standards Institute/Health Physics Society (ANSI/HPS). 2011. Criteria for performing multiple dosimetry, ANSI N13.41-2011. McLean (VA): Health Physics Society.

Beck HL, Till JE, Grogan HA, AAnenson JW, Mohler HJ, Mohler SS, Voilleque PG. 2017. Red bone marrow and male breast doses for a cohort of atomic veterans. Radiat Res. 187:221–228.

Boice JD, Jr. 2012a. A study of one million U.S. radiation workers and veterans: a new NCRP initiative. Health Phys. News XL. (11): 7–10.

Boice JD, Jr. 2012b. Study of atomic veterans who participated at U.S. aboveground atmospheric nuclear weapons tests, 1945–1962. Health Phys. News XL. (12): 6–9.

Boice JD, Jr. 2013a. Study of U.S. nuclear power plant workers. Health Phys. News XLI. (1):11–12.

Boice JD, Jr. 2013b. DOE worker studies. Health Phys. News XLI. 22–23.

Boice JD, Jr. 2013c. NCRP dosimetry committee for the Million Worker Study: Oak Ridge, Tennessee, April 2013. Health Phys. News XLI. 15–17.

Boice JD, Jr. 2014. Editorial: the importance of radiation worker studies. J Radiol Prot. 34:E7–E12.

Boice JD, Jr. 2018. The Million Person Study, Whence it came and why. Int J Radiat Biol. (submitted).

Boice JD, Jr, Cohen SS, Mumma MT, Dupree-Ellis E, Cragle DL, Eckerman KF, Wallace PW, Chadda B, Sonderman JS, Wiggs LD, et al. 2014. Mortality among Mound workers exposed to polonium-210 and other sources of radiation, 1944–1979. Radiat Res. 181:208–228.

Boice JD, Jr, Cohen SS, Mumma MT, Dupree-Ellis E, Eckerman KF, Leggett RW, Boecker BB, Brill AB, Henderson BE. 2006. Mortality among

radiation workers at Rocketdyne (Atomics International), 1948–1999. Radiat Res. 166:98–115.
Boice JD, Jr, Cohen SS, Mumma MT, Dupree-Ellis E, Eckerman KF, Leggett RW, Boecker BB, Brill AB, Henderson BE. 2011. Updated mortality analysis of radiation workers at Rocketdyne (Atomics International), 1948–2008. Radiat Res. 176:244–258.
Boice JD, Jr, Leggett RW, Dupree-Ellis E, Wallace PW, Mumma M, Cohen SS, Brill AB, Chadda B, Boecker BB, Yoder RC, et al. 2006. A comprehensive dose reconstruction methodology for former Rocketdyne/Atomics International radiation workers. Health Phys. 90:409–430.
Bouville B, Toohey RE, Boice JD, Jr, Beck HL, Dauer LT, Eckerman KF, Hagemeyer D, Leggett RW, Mumma MT, Napier B, et al. 2015. Dose reconstruction for the million worker study: status and guidelines. Health Phys. 108:206–220.
Cox DR. 1972. Regression models and life-tables. J R Stat Soc B. 34:187–220.
Dauer LT. 2014. Exposed medical staff: challenges, available tools, and opportunities for improvement. Health Phys. 106:217–224.
Dupree-Ellis E, Watkins J, Ingle JN, Phillips J. 2000. External radiation exposure and mortality in a cohort of uranium processing workers. Am J Epidemiol. 152:91–95.
Ellis ED, Boice JD, Jr, Golden AP, Girardi DJ, Cohen SS, Mumma MT, Shore RE, Leggett RW, Kerr GD. 2018. Dosimetry is key to good epidemiology: workers at Mallinckrodt Chemical Works had seven different source exposures. Health Phys. 114:386–397.
Fry SA, Dupree EA, Sipe AH, Seiler DL, Wallace PW. 1996. A study of mortality and morbidity among persons occupationally exposed to </=50 mSv in a year: Phase I, mortality through 1984. Appl Occup Environ Hyg. 11:334–343.
Gilbert ES, Cragle DL, Wiggs LD. 1993. Updated analyses of combined mortality data for workers at the Hanford Site, Oak Ridge National Laboratory, and Rocky Flats Weapons Plant. Radiat Res. 136:408–421.
Gilbert ES, Koshurnikova NA, Sokolnikov ME, Shilnikova NS, Preston DL, Ron E, Okatenko PV, Khokhryakov VF, Vasilenko EK, Miller S, et al. 2004. Lung cancer in Mayak workers. Radiat Res. 162:505–516.
Golden AP, Ellis ED, Cohen SS, Mumma MT, Leggett RW, Wallace PW, Girardi D, Watkins JP, Shore R, Boice JD. Jr. 2018. Updated mortality analysis of the Mallinckrodt uranium processing workers, 1942–2012. Int J Radiat Biol. (submitted).
International Commission on Radiological Protection (ICRP). 1995. Conversion coefficients for use in radiological protection against external radiation. ICRP Publication 74. Ann ICRP. 26(3–4):1–205.
International Commission on Radiological Protection (ICRP). 2010. Conversion coefficients for radiological protection quantities for external radiation. ICRP Publication 116. Ann ICRP. 40(2–5):1–257.
Kwon D, Hoffman FO, Moroz BE, Simon SL. 2016. Bayesian dose-response analysis for epidemiological studies with complex uncertainty in dose estimation. Statist Med. 35:339–423.
Leggett RW, Eckerman KF, Boice JD, Jr. 2005. A respiratory model for uranium aluminide based on occupational data. J Radiol Prot. 25:405–416.
Li Y, Guolo A, Hoffman FO, Carroll RJ. 2007. Shared uncertainty in measurement error problems, with application to Nevada Test Site fallout data. Biometrics. 63:1226–1236.
Linet MS, Kim KP, Miller DL, Kleinerman RA, Simon SL, de Gonzalez AB. 2010. Historical review of occupational exposures and cancer risks in medical radiation workers. Radiat Res. 174:793–808.
National Council on Radiation Protection and Measurements (NCRP). 2007. Uncertainties in the measurement and dosimetry of external radiation. Bethesda (MD): NCRP. NCRP Report No.: 158.
National Council on Radiation Protection and Measurements (NCRP). 2009a. Ionizing radiation exposure of the population of the United States. Bethesda (MD): NCRP. NCRP Report No.: 160.
National Council on Radiation Protection and Measurements (NCRP). 2009b. Radiation dose reconstruction: principles and practice. Bethesda (MD): NCRP. NCRP Report No.: 163.
National Council on Radiation Protection and Measurements (NCRP). 2009c. Uncertainties in internal radiation dose assessment. Bethesda (MD): NCRP. NCRP Report No.: 164.
National Council on Radiation Protection and Measurements (NCRP). 2010. Radiation dose management for fluoroscopically-guided interventional medical procedures. Bethesda (MD): NCRP. NCRP Report No.: 168.
National Council on Radiation Protection and Measurements (NCRP). 2012. Uncertainties in the estimation of radiation risks and probability of disease causation. Bethesda (MD): NCRP. NCRP Report No.: 171.
National Council on Radiation Protection and Measurements (NCRP). 2014. Fiftieth annual meeting program. NCRP: Achievements of the past 50 years and addressing the needs of the future. Bethesda (MD): NCRP (cited 2018 Sep 5). Available from: https://ncrponline.org/wp-content/uploads/2018/08/Annual/pp50.pdf.
National Council on Radiation Protection and Measurements (NCRP). 2018. Deriving organ doses and their uncertainty for epidemiologic studies (with a focus on the one million U.S. workers and veterans study of low-dose radiation health effects). Bethesda (MD): NCRP. NCRP Report No.: 178.
NDT Education Resource Center (NDT). 2014. Nondestructive testing. Ames (IA): Iowa State University (cited 2018 Sep 5). Available from: http://www.ndt-ed.org [accessed 2018 Sep 7].
Preston DL, Lubin JH, Pierce DA, McConney ME, Shilnikova NS. 2017. Epicure risk regression and person-year computation software: command summary and user guide. Version 2.00.03. Risk Sciences International, Ottawa, Canada. [Software]. http://epicurehelp.riskscien-ces.com [accessed 2018 September 7].
Simon SL, Hoffman FO, Hofer E. 2015. The two-dimensional Monte Carlo: a new methodologic paradigm for dose reconstruction for epidemiological studies. Radiat Res. 183:27–41.
Silver SR, Bertke SJ, Hein MJ, Daniels RD, Fleming DA, Anderson JL, Pinney SM, Hornung RW, Tseng CY. 2013. Mortality and ionising radiation exposures among workers employed at the Fernald Feed Materials Production Center (1951–1985). Occup Environ Med. 70:453–463.
Stram DO, Kopecky KJ. 2003. Power and uncertainty analysis of epidemiological studies of radiation-related disease risk in which dose estimates are based on a complex dosimetry system: some observations. Radiat Res. 160:408–417.
Stram DO, Preston DL, Sokolnikov M, Napier B, Kopecky KJ, Boice J, Beck H, Till J, Bouville A. 2015. Shared dosimetry error in epidemiological dose-response analyses. PLoS One. 10:e0119418.
Thierry-Chef I, Marshall M, Fix JJ, Bermann F, Gilbert ES, Hacker C, Heinmiller B, Murray W, Pearce MS, Utterback D, et al. 2007. The 15-Country Collaborative Study of Cancer Risk Among Radiation Workers in the Nuclear Industry: study of errors in dosimetry. Radiat Res. 167:380–395.
Tolmachev SY, Ketterer ME, Hare D, Doble P, James AC. 2011. The US Transuranium and Uranium Registries: forty years' experience and new directions in the analysis of actinides in human tissues. Proc Radiochim Acta. 1:173–181.
Till JE, Beck HL, Aanenson JW, Grogan HA, Mohler HJ, Mohler SS, Voillequé PG. 2014. Military participants at the U.S. atmospheric nuclear weapons testing—methodology for estimating dose and uncertainty. Radiat Res. 181:471–484.
U.S. Department of Energy (DOE). 2015. Occupational Radiation Exposure. Washington (DC). Department of Energy, Washington (cited 2018 Sep 5). Available from: http://energy.gov/ehss/policy-guidance-reports/databases/occupational-radiation-exposure.
U.S. Nuclear Regulatory Commission (NRC). 2011. Radiation Exposure Information and Reporting System (REIRS) for radiation workers. Washington (DC): U.S. Nuclear Regulatory Commission (cited 2018 Sep 5). Available from: http://www.nrc.gov/site-help/templates/reirs/riers.com-index.html.
Wiggs LD, Johnson ER, Cox-Devore CA, Voelz GL. 1994. Mortality through 1990 among white male workers at the Los Alamos National Laboratory: considering exposures to plutonium and external ionizing radiation. Health Phys. 67(6):577–588.
Yoder RC, Dauer LT, Balter S, Boice JD, Jr, Grogan HA, Mumma M, Passmore CN, Rothenberg LN, Vetter RJ. 2018. Dosimetry for the study of medical radiation workers with a focus on the mean absorbed dose to the lung, brain and other organs. Int J Radiat Biol. (submitted).