The Confusing World of Radiation Dosimetry - 9444

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ABSTRACT

This paper reviews the different methods for calculating radiation doses to workers and the public that are either in use in the United States today or under consideration, with particular emphasis on methods for determining internal doses following intake of radionuclides. Internal dose methods range from critical organ dose, as determined using Publication 2 of the International Commission on Radiological Protection (ICRP), published in 1959, to the most recent method for determining effective dose, as found in ICRP Publication 103, published in 2008. Any change in radiation dosimetry methodology can change the dose of record for an individual, particularly when considering intakes of radionuclides. Updating the dosimetry method used in the U.S. would also affect dose-based compliance calculations. Calculations using the historic and current dosimetry methods of the ICRP are presented to illustrate how the relationship between activity concentration and dose changes for a number of important radionuclides and exposure pathways.

DISCLAIMER

The opinions expressed in this paper are those of the author and do not necessarily reflect those of the United States Environmental Protection Agency.

INTRODUCTION

In 2008, the International Commission on Radiological Protection (ICRP) issued its new general recommendations in Publication 103 (ICRP 103). [1] These recommendations updated the previous recommendations issued as Publication 60 (ICRP 60) in 1991. [2] Coincidentally, it was in 1991 that the U.S. Nuclear Regulatory Commission (NRC) completed work on the last major revision of its "Standards for Protection against Radiation" found at 10 CFR part 20. [3] The multi-year effort that resulted in the new NRC regulations was a move from the old ICRP Publication 2 (1959) system of dosimetry based on critical organ doses to the newer ICRP Publication 26 (ICRP 26, 1976) system of dosimetry using the double weighted quantity, effective dose equivalent. [4, 5] Largely as a result of unfortunate timing, the United States has been out of step with the ICRP recommendations for calculating radiation doses to humans for almost 20 years, and in some cases we are 50 years behind the times.

In its simplest form, radiation dose is a physical, measurable quantity called absorbed dose. Absorbed dose is the amount of radiation energy deposited in a unit mass of tissue. Absorbed dose is measured in SI units of grays or in traditional units of rads (1 gray = 100 rads). Absorbed dose is an inadequate surrogate for managing radiation risk because different types of radiation cause differing degrees of biological harm for the same amount of absorbed dose. To account for this difference, absorbed dose is adjusted by a radiation weighting factor, W_R, such that the absorbed dose x W_R = equivalent dose. The radiation weighting factor is assigned a value of 1 for beta and gamma radiation, but for alpha radiation, $W_R = 20$. Equivalent dose is measured in SI units of sieverts or in traditional units of rems (1 sievert = 100 rems). One milligray of beta or gamma radiation gives a 1 millisievert equivalent dose, whereas 1 milligray of alpha radiation gives a 20 millisievert equivalent dose.

As is the case for absorbed dose, equivalent dose is also an inadequate surrogate for assessing radiation risk. Equivalent dose only accounts for differences in the ability of the different types of radiation (alpha,

beta and gamma) to cause biological harm. In 1977, the International Commission on Radiological Protection (ICRP) introduced a second dose modifying factor, the tissue weighting factor, or W_T. The W_T is needed because, for the same equivalent dose, different organs show different susceptibility to radiation-induced cancers. The W_T is only needed to account for non-uniform external irradiation or for internal contamination where different organs receive different doses. Compliance with dose limits under this system is determined by summing the tissue weighted equivalent doses to a specified set of organs and tissues thought to be most susceptible to radiation-induced cancer. An organ dose multiplied by its tissue weighting factor gives the "effective" uniform dose to the whole body that would give the same risk of cancer and genetic harm as that organ dose. By definition, the sum of all the tissue weighting factors must equal 1. Following modifications to this system in 1990, the dose quantity calculated in this manner is now called the effective dose.

The dose-based regulatory structure for radiation protection in the United States today is complicated. The U.S. Environmental Protection Agency (EPA) and the NRC still have regulations in place that require use of the ICRP 2 methodology, but for the most part their dose-based regulations follow ICRP 26. The Occupational Safety and Health Administration's (OSHA) radiation protection regulations continue to be based on ICRP 2. The Department of Energy has recently adopted an ICRP 60 approach for calculating the doses to its workers. Europe, along with most other countries with radiation protection programs, has adopted ICRP 60. It is expected that these countries will now begin the process of adopting ICRP 103.

The dosimetry changes from ICRP 26 to ICRP 103 included both changes in the values of the radiation and tissue weighting factors and changes in the underlying biokinetic models used to determine organ doses following intakes of radionuclides. Changes to the biokinetic models since ICRP 26 have included a new respiratory tract model (ICRP Publication 66) and more recently, a new human alimentary tract (HAT) model (ICRP Publication 100). [6, 7] The biokinetic models can have a major impact on the calculated effective dose, but their importance is often invisible to the person calculating a dose, because they are incorporated into the dose conversion factors (DCFs) associated with each set of ICRP Recommendations. The DCFs allow measured or modeled radionuclide-specific activity concentrations in air and water to be easily converted into organ doses. ICRP 26 DCFs are published as ICRP Publication 30 for adult workers. [8] ICRP 60 DCFs are summarized in ICRP Publication 68 (for adult workers) and in ICRP Publication 72 (for the public). [9, 10] The DCFs for ICRP 103 will be published over the next several years. The updated respiratory tract model was included in ICRP 68 and 72. The new HAT model is expected to be incorporated in the forthcoming sets of DCFs for ICRP 103.

In the move from ICRP 26 to ICRP 60, the dose quantity previously named effective dose equivalent (H_E) was renamed effective dose (E) . As described by Eckerman and Leggett at Oak Ridge National Laboratory, "In contrast to the definition of the effective dose equivalent *HE*, the weighting factors W_T in the equation for the effective dose *E* are not specified as part of the definition of *E* but can take any assigned values. Thus, the effective dose equivalent, *HE*, may be interpreted as a special case of the effective dose, *E*." [11] Whether you refer to a person's radiation dose as effective dose, effective dose equivalent, or, as sometimes used in the U.S., total effective dose equivalent, the concept is the same – a measure of absorbed dose weighted by the type of radiation and the radiosensitivity of each exposed organ summed over all specified organs and, for internal emitters, a dose commitment period. Again, the problem that we have in the United States is that the measure of regulatory compliance for dose-based rules depends on which regulation is being enforced and which of the various systems of dosimetry is referenced in the rule.

REGULATIONS BASED ON CRITICAL ORGAN DOSE (ICRP 2)

Maximum Contaminant Levels (MCLs) for manmade beta/photon emitters

The Safe Drinking Water Act (SDWA) gives EPA the authority to set MCLs for public drinking water systems. For manmade beta/photon emitters, that limit is 40 microsieverts per year (originally stated as 4 millirems/y, using traditional units) to the critical organ, using old National Bureau of Standards (NBS) values derived from ICRP 2 methodology (NBS Handbook 69, 1959 and its Addendum 1, 1963). [12] When these first drinking water standards for radionuclide contaminants were promulgated in 1976, critical organ dose was still the accepted method for managing radiation dose to internal organs. Though the concept of effective dose equivalent was introduced in ICRP 26 the next year, it was too late to affect the safe drinking water MCLs.

When EPA updated the MCLs in 2000, an earlier 1991 proposal to adopt a 4 millirem effective dose equivalent standard was rejected. In explaining the decision, EPA stated:

> In summary, the Agency fully recognizes that the dose-based MCL of 4 mrem/year is based on older scientific models. However, the Agency has decided to retain the current MCL given that:
> - Federal Guidance Report 13 (FGR–13, EPA 1999b) demonstrates that the 1991 proposed MCL of 4 mrem-ede/year results in concentration limits that are outside the 10^{-6} to 10^{-4} range;
> - FGR–13 demonstrates that the current MCL of 4 mrem/year results in concentration limits that are within the 10^{-6} to 10^{-4} range;
> - the fact that there is no evidence of appreciable occurrence of man-made beta emitters in drinking water;
> - the 1996 Safe Drinking Water Act requires EPA to evaluate all NPDWRs every six years (''Six Year Review''). EPA believes that Six Year Review is the appropriate vehicle for updating the beta particle and photon radioactivity MCL. [13]

Under the SDWA, EPA determined that the Maximum Contaminant Level Goal (MCLG) for any carcinogen should be 0. Since most drinking water systems are now easily meeting the manmade beta/photon MCLs, it can be argued that there is little incentive to relax them. Also, the 1996 revisions to SDWA do not permit revisions to MCLs that do not "maintain, or provide for greater protection of health."

Maximum permissible concentrations for airborne radionuclides

Most occupational exposure to radiation is regulated by either the NRC or its Agreement States. For certain occupations that fall outside their authority, the standards of the Occupational Safety and Health Administration (OSHA) may apply. These standards are now found at 29 CFR 1910.1096. [14] Workers subject to OSHA radiation protection standards include those exposed to industrial x-rays, accelerator-produced radiation, and technologically-enhanced naturally occurring radioactive material (TENORM). When the OSHA regulations were issued in 1971, they were essentially identical to the NRC's regulations found at 10 CFR part 20. In 1991, the NRC revised their regulations to be compatible with ICRP 26, but OSHA has retained their old regulations.

For protecting workers from airborne radioactivity, the NRC refers licensees to Table I of 10 CFR 20, Appendix B, where one column includes derived air concentrations for individual radionuclides. [3] Each value in this column, given in microcuries per milliliter of air (μCi/ml), represents the concentration of a radionuclide that would give an internal dose of 5 rems per year if breathed for 2000 hours (i.e., a work-year), based on ICRP 26. Prior to 1991, the values in Appendix B were based on ICRP 2. On the OSHA web site, there is a Standards Interpretation letter to the Corps of Engineers, dated Dec. 23, 2002 that states, "Case law supports the interpretation that the original version of a referenced federal regulation is the enforceable regulation. Therefore, the 1969 version of Appendix B to 10 CFR Part 20 that was referenced in the original OSHA ionizing radiation standard in 1971 is enforceable…"[15] As a result,

employers responsible for assuring compliance with OSHA's maximum permissible concentrations (MPCs) for airborne radioactivity must use these older standards. While the values are often the same, there are some important discrepancies between these two sets of values, as shown in Table 1. The NRC's limit for radon is 1/3 the OSHA limit and the limit for Pu-241 is less than 1% the OSHA limit. On the other hand, the NRC limit for I-134 is 40 times less stringent than OSHA's, which may be explained by the next example.

Table 1. Comparison of Current NRC Derived Air Concentrations (DACs) and OSHA Maximum Permissible Concentrations (MPCs) for Selected Radionuclides

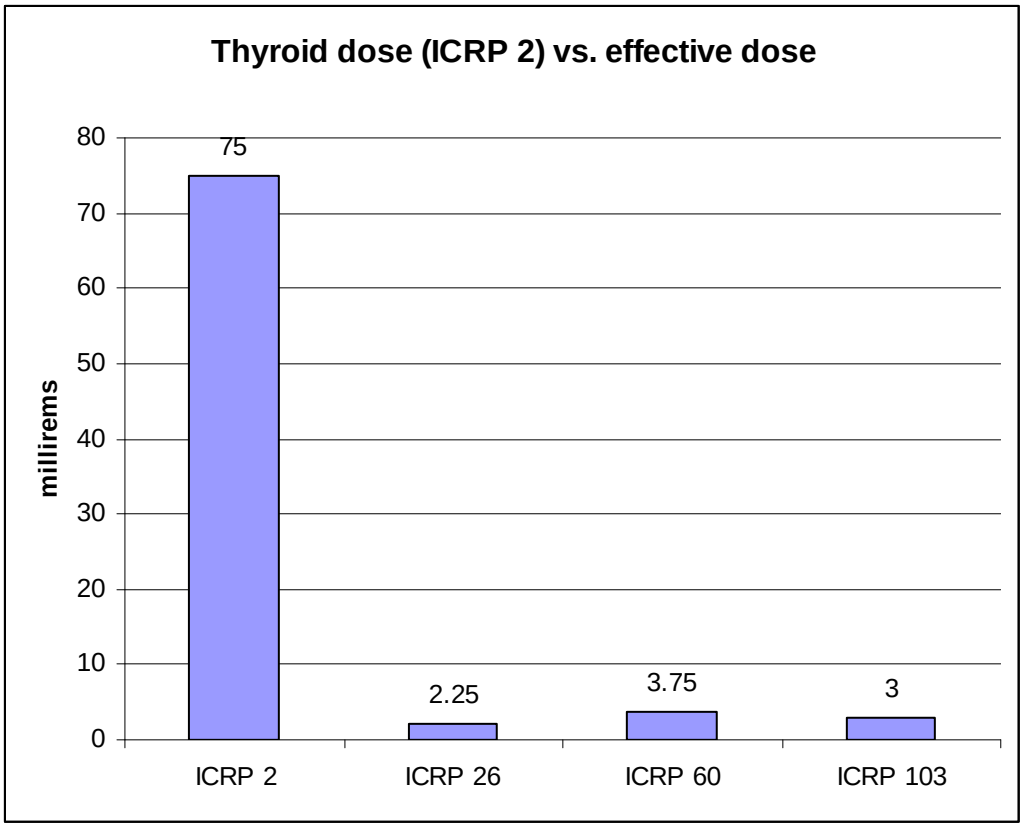
Radionuclide	NRC DAC (2008) (μCi/ml)	OSHA MPC (1971) (μCi/ml)	Ratio NRC:OSHA
Rn-222 + D	3×10^{-8}	1×10^{-7}	0.3
I-134 (S)*	2×10^{-5}	5×10^{-7}	40
Cs-137	6×10^{-8}	6×10^{-8}	1
Pu-241 (I)*	3×10^{-10}	4×10^{-8}	0.0075

* S is the soluble form of a radiochemical and I is the insoluble form

Uranium fuel cycle regulations and thyroid dose

In 1977, EPA published standards for the uranium fuel cycle at 40 CFR 190.10. For normal operations, the rule states that operations should be conducted to provide reasonable assurance that "the annual dose equivalent does not exceed 25 millirems to the whole body, 75millirems to the thyroid, and 25 millirems to any other organ of any member of the public as the result of exposures to planned discharges of radioactive materials…" [16] By setting a higher dose limit for the thyroid, EPA acknowledged that the risk per unit dose to different organs could vary substantially. However, as shown below, this allowance still equates to a very stringent requirement for the thyroid. Figure 1 shows what the 0.75 millisievert (i.e., 75 millirem) thyroid dose equates to, using the thyroid tissue weighting factors from ICRP 26 (0.03), ICRP 60 (0.05), and ICRP 103 (0.04). The first column (thyroid organ dose) assumes a tissue weighting factor of 1 for comparison.

Figure 1. Comparison of effective thyroid doses from an organ dose of 75 millirems



As this chart strikingly demonstrates, a dose to the thyroid of 0.75 millisieverts (75 millirems) gives an effective dose of only 30 microsieverts (3 millirems), based on the latest ICRP recommendations. For fuel cycle facilities that experience iodine releases, the thyroid dose limit in 40 CFR part 190 is far more restrictive, from an effective dose standpoint, than the 0.25 millisievert (25 millirems) whole body dose limit. Using the 0.25 millisievert (25 millirems) whole body standard as a reference, and the latest thyroid tissue weighting factor from ICRP 103 (0.04), the dose limit for the thyroid based on a 0.25 millisievert effective dose would be 6.25 millisieverts (625 millirems).

REGULATIONS BASED ON EFFECTIVE DOSE (ICRP 26, 60, or 103)

Effective dose is a practical way to measure compliance with regulatory dose limits, especially when different organs receive different doses. As described in the Introduction, the dose that an organ receives following a known intake of a radionuclide is usually estimated by using a pathway- and radionuclide-specific DCF. For situations where relatively uniform external gamma fields are the predominant exposure pathway, the value of effective dose is robust and largely insensitive to changes in the values of the tissue weighting factors. However, when internal pathways are dominant, the effect of changing a value for a tissue weighting factor can also be significant.

The effect of DCFs on effective dose

The current NRC regulations for radiation protection (10 CFR part 20) are based on ICRP 26 and incorporate DACs and ALIs from EPA's Federal Guidance Report 11 (FGR 11), "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion."[17] FGR 11 incorporates the biokinetic models in ICRP 30. Following the release of ICRP

60 and the new respiratory tract model, ICRP published new derived dose conversion factors for workers in ICRP 68. For those NRC licensees whose employees are largely exposed to external gamma radiation, moving to ICRP 68-based dosimetry would not make much difference in the recorded occupational doses for their employees. However, the new biokinteic models incorporated in ICRP 68 do result in significant changes in calculated effective dose for intakes of several important radionuclides. Table 2 shows the ratio of effective dose calculated using DCFs in FGR 11 (representing ICRP 30) and ICRP 68 for a few of these radionuclides. ICRP 68 recommends a default particle size of 5 microns Activity Median Aerodynamic Diameter (AMAD) and ICRP 30 uses a 1 micron AMAD. These particle sizes are reflected in the following data.

Table 2: Ratio of $E:H_E$ for selected radionuclide DCFs for inhalation

Radionuclide	Effective Dose (E) ICRP 68 (Sv/Bq)	Effective Dose Equivalent (H_E) FGR 11 (Sv/Bq)	Ratio $E:H_E$
Th-232	1.2×10^{-5} (S)*	3.11×10^{-4} (Y)**	0.04
Np-237	1.5×10^{-5} (M)	1.46×10^{-4} (W)	0.10
Pu-239	8.3×10^{-6} (S)	8.33×10^{-5} (Y)	0.10

*Respiratory tract absorption rates are Fast (F), Medium (M) and Slow (S)
** Respiratory tract clearance classes are Days (D), Weeks (W) and Years (Y)

Not surprisingly, some fuel cycle licensees were anxious to take advantage of this improved dosimetry. In 1999, the NRC Commissioners approved a request from a licensee, whose employee's mainly handled thorium, for an exemption from 10 CFR part 20 to allow them to take advantage of the updated dosimetry. [18] The Commission approved the request and further stated that it would approve additional exemption requests of this type on a case-by-case basis, without initiating any changes to 10 CFR part 20.

The effect of tissue weighting factors on effective dose

In ICRP 26, quantities for the tissue weighting factor were strictly defined. In successive revisions to the general recommendations (ICRP 60 and 103), the ICRP has stated that the values of W_T can be adjusted as new scientific data is available, although recommended tables of W_T's are provided. Table 3 shows how the recommended tissue weighting factors have changed over time.

Several observations can be made about the data in this table. It is noted that the ICRP has been steadily increasing the number of organs for which W_T's are provided. Between ICRP 26 and 60, there was a 3-fold decrease in the W_T for bone surface. As a result, for transuranic bone-seeking radionuclides, moving to the newer ICRP dosimetry would reduce the calculated bone surface dose per unit of intake.

Table 3: Comparison of W_T Values Across ICRP Publications

ORGAN	**ICRP 26**	**ICRP 60**	**ICRP 103**
Bone marrow (red)	0.12	0.12	0.12
Colon	-	0.12	0.12
Lung	0.12	0.12	0.12
Stomach	-	0.12	0.12
Breast	0.15	0.05	0.12
Gonads	0.25	0.20	0.08
Bladder	-	0.05	0.04
Esophagus	-	0.05	0.04
Liver	-	0.05	0.04
Thyroid	0.03	0.05	0.04
Bone Surface	0.03	0.01	0.01

Brain	-	-	0.01
Salivary Gland	-	-	0.01
Skin	-	0.01	0.01
Remainder Tissues	0.30	0.05	0.12
TOTAL	**1.00**	**1.00**	**1.00**

Between ICRP 60 and 103, the W_T for gonads dropped significantly, reflecting a judgment by the ICRP that the genetic detriment is not as large as previously estimated. There was also a significant rise in the W_T for breasts, reflecting the epidemiological evidence for increased radiogenic breast cancer risk.

For radionuclides that distribute fairly uniformly across tissues following ingestion or inhalation, the effect of changes to the W_T on effective dose is minimal. However, for those radionuclides that concentrate in certain organs, like radium, strontium, and actinides in bone or iodine in the thyroid, changes to the W_T's can have a significant impact on the calculated effective dose,

CONCLUSIONS

The examples given in this paper have been chosen to highlight particularly noteworthy differences across the various methods of estimating dose to humans. Moving from ICRP 2 to ICRP 103, there has not been a consistent trend towards decreasing or increasing doses for all radionuclides. As biokinetic models have improved, dosimetry systems have become better able to associate intakes of radionuclides with organ doses and effective doses.

For students graduating in health physics today, or nuclear workers relocating to the United States from Europe or Asia, their employers will need to train them in systems of dosimetry going back 50 years. It may be time for the U.S. to seriously consider adopting the latest system of dosimetry recommended by the ICRP. The U.S. could accomplish this over the next 5 to 10 years, along with much of the rest of the world. If the updated recommendations of the ICRP continue to be issued about every 20 years, the U.S. could look forward to a lengthy period of stability and international consistency in the way radiation doses to humans are calculated and compared.

REFERENCES

1. International Commission on Radiological Protection, 2008, Recommendations of the International Commission on Radiological Protection, ICRP Publication 103 (Pergamon Press, Oxford).
2. International Commission on Radiological Protection, 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60 (Pergamon Press, Oxford).
3. Title 10, Code of Federal Regulations (U.S. Government Printing Office, Washington).
4. International Commission on Radiological Protection, 1959, Report of Committee II on Permissible Dose for Internal Radiation, ICRP Publication 2 (Pergamon Press, London).
5. International Commission on Radiological Protection, Annals of the ICRP, ICRP Publication 26 (Pergamon Press, Oxford).
6. International Commission on Radiological Protection, 1995, Human Respiratory Tract Model for Radiological Protection, ICRP Publication 66 (Pergamon Press, Oxford).
7. International Commission on Radiological Protection, 2007, Human Alimentary Tract Model for Radiological Protection, ICRP Publication 100 (Pergamon Press, Oxford).
8. International Commission on Radiological Protection, 1979, Limits of Intakes of Radionuclides by Workers, ICRP Publication 30 (Pergamon Press, Oxford).

9. International Commission on Radiological Protection, 1995, Dose Coefficients for Intakes of Radionuclides by Workers, ICRP Publication 68 (Pergamon Press, Oxford).
10. International Commission on Radiological Protection, 1996, Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 5: Compilation of Ingestion and Inhalation Dose Coefficients, ICRP Publication 72 (Pergamon Press, Oxford).
11. R.W. LEGGETT and K.F. ECKERMAN, p.3, "Dosimetric Significance of the ICRP's Updated Guidance and Models, 1989-2003, and Implications for U.S. Federal Guidance," ORNL/TM-2003/207, Oak Ridge National Laboratory, (2003).
12. U.S. Department of Commerce, National Bureau of Standards, 1959 (with addendum in 1963), Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure – Handbook 69 (U.S. Government Printing Office, Washington).
13. U.S. Environmental Protection Agency, National Primary Drinking Water Regulations; Radionuclides; Notice of Data Availability, April 21, 2000, Federal Register, Vol. 65, p. 21583.
14. Title 29, Code of Federal Regulations (U.S. Government Printing Office, Washington).
15. Occupational Safety and Health Administration, Standards Interpretation Letter from Mr. Richard Fairfax (OSHA) to Ms. Connie DeWitte (U.S. Army Corps of Engineers), Dec. 23, 2002 (available at www.osha.gov).
16. Title 40, Code of Federal Regulations, part 190, section 10 (U.S. Government Printing Office, Washington).
17. U.S. Environmental Protection Agency, Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion, Federal Guidance Report No. 11, EPA-520/1-88-020, 1988.
18. U.S. Nuclear Regulatory Commission, SRM-SECY-99-077, April 21, 1999 (www.nrc.gov).