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APPROPRIATE USE OF EFFECTIVE DOSE IN RADIATION PROTECTION AND RISK ASSESSMENT

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Abstract

Effective dose was introduced by the ICRP for the single, over-arching purpose of setting limits for radiation protection. Effective dose is a derived quantity or mathematical construct and not a physical, measurable quantity. The formula for calculating effective dose to a reference model incorporates terms to account for all radiation types, organ and tissue radiosensitivities, population groups, and multiple biological endpoints. The properties and appropriate applications of effective dose are not well understood by many within and outside the health physics profession; no other quantity in radiation protection has been more confusing or misunderstood. According to ICRP Publication 103, effective dose is to be used for “prospective dose assessment for planning and optimization in radiological protection, and retrospective demonstration of compliance for regulatory purposes.” In practice, effective dose has been applied incorrectly to predict cancer risk among exposed persons. The concept of effective dose applies generally to reference models only and not to individual subjects. While conceived to represent a measure of cancer risk or heritable detrimental effects, effective dose is not predictive of future cancer risk. The formula for calculating effective dose incorporates committee-selected weighting factors for radiation quality and organ sensitivity; however, the organ weighting factors are averaged across all ages and both genders and thus do not apply to any specific individual or radiosensitive subpopulations such as children and young women. Further, it is not appropriate to apply effective dose to individual medical patients because patient-specific parameters may vary substantially from the assumptions used in generalized models. Also, effective dose is not applicable to therapeutic uses of radiation, as its mathematical underpinnings pertain only to observed late (stochastic) effects of radiation exposure and do not account for short-term adverse tissue reactions. The weighting factors incorporate substantial uncertainties, and linearity of the dose-response function at low dose is uncertain and highly disputed. Since effective dose is not predictive of future cancer incidence, it follows that effective dose should never be used to estimate future cancer risk from specific sources of radiation exposure. Instead, individual assessments of potential detriment should only be based on organ or tissue radiation absorbed dose, together with best scientific understanding of the corresponding dose-response relationships.

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Keywords

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INTRODUCTION

The purpose of this article is to help the radiation protection community better understand the meaning and correct use of the quantity “effective dose,” its limitations, correct and incorrect applications, and potential misuses. The properties and appropriate applications of effective dose are not well understood by many within and outside the health physics profession; no other quantity in radiation protection has been more confusing or misunderstood (Boyd 2009).

The term “effective dose” implies a known relationship between measured physical quantities and biological effect. Dosimetry is fundamental to radiation protection planning, assessment of biological effects, and monitoring compliance with radiation exposure limits. The radiation dose, or quantity of energy imparted per unit mass of an absorbing medium, can be measured or directly biological effects, and monitoring compliance with radiation exposure limits. The radiation dose, air kerma, and particle fluence.

Radiation protection professionals define radiation absorbed dose and dose rate using carefully defined quantities and units for applications to occupational, environmental, and medical exposures. Two international scientific bodies provide the terms and definitions used in dosimetry. The International Commission on Quantities and Units (ICRU) develops recommendations on radiation quantities and units, terminology, measurement procedures, and reference data. Similarly, the International Commission on Radiological Protection (ICRP) develops the international system of radiological protection used as the common basis for radiological protection standards, legislation, guidelines, programs, and practices. Radiation protection quantities fall into three distinct groupings:

1. Physical and measurable quantities (such as absorbed dose, photon exposure in air, air kerma); and
2. Derived quantities (not measured directly but based on a measurement multiplied by other factors, including equivalent dose, effective dose, and dose equivalent); and
3. Values determined by scientific committee (such as radiation weighting factors, tissue weighting factors, and the primary and secondary radiation limits).

Definitions of radiation quantities and units evolved over time, and recent definitions are given in ICRU and ICRP publications (ICRU 2011; ICRP 2007). Two of these quantities have been particularly confusing (Brenner 2008) to radiation protection specialists and non-experts alike as to what they represent and how they should be properly used: equivalent dose and effective dose. Effective dose was introduced by the ICRP for the single, overarching purpose of setting limits for radiation protection (Paquet et al. 2016). Effective dose is a derived quantity, or mathematical construct, and not a physical, measurable quantity. The formula for calculating effective dose to a reference model incorporates terms to

account for all radiation types, organ and tissue radiosensitivities, population groups, and multiple biological endpoints. This manuscript provides additional clarification on appropriate and inappropriate use of effective dose for a broad range of applications.

DEFINITIONS

The basic quantities described below include (1) absorbed dose, (2) equivalent dose, and (3) effective dose. A few comments are also included on historical evolution of these quantities.

Absorbed dose

Absorbed dose is the fundamental radiation quantity that describes energy deposition by ionizing radiation in an absorbing medium; absorbed dose applies to all radiation exposures, all types of ionizing radiation, any absorbing medium, and all biological targets and geometries. In its simplest constitution, the absorbed dose is energy imparted per unit mass, or $D(r_T) = \epsilon(r_T)/m(r_T)$, where $\epsilon(r_T)$ is the mean energy imparted to a target region (r_T), and $m(r_T)$ is the mass of the absorbing medium. The units of absorbed dose are joule per kilogram (J kg^{-1}) in the International System of Units (SI), where the special name for the unit of absorbed dose is gray (Gy), and 1 Gy equals exactly 1.0 J kg^{-1} .

Absorbed dose may be defined at a point or may be averaged over a mass of absorbing medium. Absorbed dose is related to the number of ionization events in the target region, and ionization events are related to physical damage caused. When dose and effects are correctly assessed, the absorbed dose correlates well with biological effects such as adverse tissue reactions and tumor cell killing. Absorbed dose is often correlated with delayed effects (long latent period), cumulative effects (protracted exposure over long periods), and stochastic effects (from short-term or ongoing exposures), such as the probability of cancer induction.

Equivalent dose

The equivalent dose $H(r_T, \tau)$ to an organ or tissue r_T is a derived quantity used in radiation protection for calculating whole-body effective dose (ICRP 1991, 2007, 2015). The equivalent dose is the product of the mean absorbed dose to an organ or tissue and applicable radiation weighting factors (w_R). Equivalent dose is computed as the sum of absorbed doses in an organ or tissue from all contributions by radiations of different types $D_R(r_T, \tau)$ multiplied by their respective radiation qualities w_R :

$$H(r_T, \tau) = \sum_R w_R D_R(r_T, \tau). \quad (1)$$

The units of equivalent dose are joule per kilogram (J kg^{-1}), where the special name for the unit of equivalent dose is sievert (Sv, J kg^{-1}) (ICRP 2015).

By definition (ICRP 2007), the concept of equivalent dose applies only to stochastic effects and population group averages (reference models) for radiation protection planning and not to individual subjects for risk assessment. By extension, equivalent dose is not defined for short-term adverse tissue reactions (deterministic effects) in radiobiology; it is not the same

as “dose equivalent.” Quoting from ICRP Publication 103 (ICRP 2007, p.61): “The radiation weighting factors for radiations characterised by a high linear energy transfer, so-called high-LET radiations (see Section 4.3.3), are derived for stochastic effects at low doses”.

These definitions show that Gy is the unit given for measurable or calculated quantities of absorbed dose and kerma and that Sv is used only for quantities derived from absorbed dose. The special unit Sv implies that equivalent dose is an intermediate quantity for calculating effective dose—applicable only to late stochastic effects (cancer and hereditary damage) and not to immediate deterministic effects (Harrison et al. 2016). Conceptual problems and definition conflicts arise when the quantity equivalent dose (Sv) is incorrectly applied to situations where the implied biological endpoint is not cancer or hereditary damage, such as expressing radiation exposure limits using equivalent dose for protecting the skin, hands and feet, and eyes [as in ICRP Publication 60 (1991) and retained in ICRP Publication 103 (2007)]. Limits to avoid deterministic effects to the hands and feet, lens of the eye, and skin would more appropriately be set in terms of the quantity absorbed dose (Gy) rather than equivalent dose (Sv) (Harrison et al. 2016).

Historical evolution of equivalent dose

Equivalent dose evolved from the 1957 definition of RBE dose (an absorbed dose multiplied by an observed relative biological effectiveness factor) (ICRU 1957). The RBE dose became the dose equivalent (ICRP 1977); that is, the product of (1) the absorbed dose, (2) a quality factor, and (3) any other modifying factors associated with delayed stochastic effects (ICRP 1977) to account for dose rate and the microscopic distributions of energy deposition. The quality factor (Q) was based on the collision-stopping power in water at a point of interest (in keV per μm) but was simplified to values of 1 for x rays, gamma rays, and electrons; 10 for neutrons and protons; and 20 for alpha particles.

During the evolution of units from publications ICRP 26 to ICRP 60, dose equivalent was assigned the special unit Sv representing a physical quantity multiplied by subjective factors. In ICRP Publication 60 (1991), dose equivalent became equivalent dose as an intermediate quantity for the singular purpose of calculating effective dose, while dose equivalent was retained as an “operational quantity.” Both equivalent dose and dose equivalent retained the unit Sv. Dose equivalent is absorbed dose multiplied by a quality factor (Q), whereas equivalent dose is absorbed dose multiplied by radiation weighting factors (w_R). An underlying assumption is that stochastic effects of low-dose radiation increase linearly with dose equivalent and equivalent dose. Quoting directly from ICRP 103 (2007, p. 510): “It is scientifically plausible to assume that the incidence of cancer or heritable effects will rise in direct proportion to an increase in the equivalent dose in the relevant organs and tissues.”

Effective dose

Effective dose is a mathematical construct, concept, or surrogate of risk, used in radiation protection as the basis for calculating annual radiation limits to workers and members of the public from exposure to radiation and intakes of radionuclides. Effective dose is also used for comparing an assigned occupational dose of record to radiation protection standards. Thus, effective dose is not a real radiation dose to a person per se, but rather is a computed

number representing an approximate measure of stochastic risk applied to a representative model (Paquet et al. 2016). According to ICRP Publication 103 [ICRP 2007, paragraph (i), p. 13]: “Effective dose is calculated for a Reference Person and not for an individual.”

The reference model is averaged as a hybrid reference (50th percentile) male and female representing all ages and sizes in a standard population (ICRP 2015):

$$E = \sum_T W_T \left[\frac{H(r_T, \tau)^{male} + H(r_T, \tau)^{female}}{2} \right]. \quad (2)$$

The units of effective dose E are joule per kilogram (J kg^{-1}), where the special named unit for effective dose is Sv.

Tissue weighting factors (w_T) are assigned a priori by committee (ICRP 2007) for organs and tissues (r_T) of the body and are subject to evolutionary revision. Tissue weighting factors represent approximate relative contributions of tissue radiosensitivity to the assumed total risk of radiation detriment for stochastic effects after exposure to radiation (based on the Japanese atomic bomb survivor epidemiology). The sum of all the hypothetical tissue weighting factors equals 1.0. However, the tissue weighting factors were assigned by an expert panel as a simple set of values. Although the factors are based on the current understanding of stochastic risk, they do not fully reflect scientific knowledge of radiation risks (Harrison and Lopez 2015).

Equation 2 shows that effective dose is calculated using a hybrid Reference Person model by first calculating all the organ equivalent doses $H(r_T, \tau)$, averaging for male and female values, with each organ weighted according to a tissue weighting factor, and then summing all the doubly-weighted organ equivalent doses (ICRP 2015). The calculations are complex for radionuclide intakes because an absorbed dose $D(r_T)$ for each organ or tissue must first be calculated using the appropriate biokinetic uptake and excretion model for the specific radionuclide and chemical form using all relevant bioassay and metabolic data (ICRP 2015). Thus, effective dose is a doubly-weighted construct or surrogate of risk calculated for a population-average reference model, with adjustments for chemical form, metabolic/biokinetic radionuclide behaviors, and modes of intake and excretion—assuming strict applicability of the linear no-threshold dose response hypothesis for stochastic effects; hence, effective dose is not a purely physical quantity (ICRP 1991, 2007, 2015). Further, ICRP 103 (2007) states: “In the definition and calculation of effective dose, the recommended radiation weighting factors, w_R , allow for the differences in the effect of various radiations in causing stochastic effects while tissue weighting factors, (w_T), allow for the variations in radiation sensitivity of different organs and tissues to the induction of stochastic effects.”

Assumptions built into the model and formula for calculating effective dose are many, and substantial uncertainties apply to each assumption. The model assumes or implies that:

- Stochastic risks follow the linear no-threshold dose response hypothesis at all dose levels, and linearity is assumed for radiological protection purposes (without direct evidence at dose level below 100 mGy or 100 mSv);
- Stochastic risks for internal radionuclides are equivalent per unit dose, as also for instantaneous external exposure to mixed radiation types (such as gamma rays and neutrons);
- Stochastic risks for individual organs are equivalent whether irradiated uniformly or non-uniformly;
- Stochastic risks for non-uniform radionuclide distributions are equivalent to those of a uniformly irradiated whole body;
- External dose from penetrating radiation may be summed with internal dose from radionuclides in the body;
- Stochastic risks per unit dose are equivalent for all ages and both genders, including children and young women;
- Radiation weighting factors are assumed for stochastic effects with very long latent periods;
- Stochastic risks are not modulated by dose rate, adaptive response, cellular repair of sub-lethal radiation damage, or genomic instability over long time periods (years); and
- Tissue weighting factors are assumed for the small organ subset represented in the model and adequately address or apply to more than 250 types of cancer that may be radiation-induced.

Since the selection of tissue weighting factors as measures of relative detriment representing all population groups implies a high degree of uncertainty in the values selected for each organ or tissue (ICRP 2007; Paquet et al. 2016), it follows that the risk coefficients underlying effective dose in eqn (2) do not apply to individual risk and do not predict future risk of cancer or hereditary damage. For example, with ^{131}I uptake in the thyroid, no published data show any correlation between calculated effective dose with the $5\% \text{ Sv}^{-1}$ risk coefficient applied, and reported incidence of thyroid cancer.

Historical evolution of effective dose

Recognizing that the absorbed dose was insufficient to predict either the probability or severity of radiation health effects, the concept of a weighted mean whole-body dose equivalent was introduced (but not named) in ICRP Publication 26 (paragraphs 104-105; ICRP 1977). It was referred to as the doubly weighted absorbed dose, the effective dose equivalent, or the committed effective dose equivalent (for internal emitters). For simplicity, the name “effective dose” was given in ICRP Publication 28 (ICRP 1978). Whereas the dose equivalent (in Sv) may have applied to deterministic effects as well as delayed stochastic effects, the new quantity effective dose employed only radiation and tissue weighting factors applicable to stochastic effects (cancer and hereditary changes) at low doses (ICRP 1977, 1978, 1991). Although ICRP assigned the unit of effective dose the special name sievert

(with physical dimensions in joules per kilogram), effective dose was never a physical quantity; rather, it was a mathematical concept and the product of three entities: (1) a physical quantity (absorbed dose), (2) a construct of relative biological effectiveness by radiation type (the radiation weighting factor) for cancer induction, and (3) a construct of the relative frequency of cancer occurring in each organ after whole-body radiation exposure (the tissue weighting factor). The magnitude of the radiation and tissue weighting factors have been set by expert panels based on current understanding of stochastic risk and, thereby, are subject to change (Table 1). The nominal risk coefficients underlying the concept of effective dose assume validity of the linear no-threshold dose-response relationship and neglect both dose-rate effects and variability in biological response due to non-uniform depositions of internal radionuclides in tissues. Since the weighting factors incorporate substantial uncertainties, particularly for the low doses routinely encountered in occupational radiation protection and diagnostic radiology, and since linearity of the dose-response function at low dose is highly debated, the ICRP (2007) reaffirmed that “many uncertainties pertain to the nominal factors used to assess effective dose.”

APPLICATION OF RADIATION PROTECTION QUANTITIES IN MEDICINE

Evolutionary changes in dose quantities raised questions for medical applications and internal radiation dosimetry for medically administered radiopharmaceuticals for beneficial diagnostic and therapeutic applications. In 1993, writing for the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine, Poston (1993) stated that the effective dose equivalent (now effective dose) “is inappropriate in dose calculations associated with nuclear medicine patients” for five primary reasons: (1) it was intended by ICRP for occupational radiation protection applications and not for assessing risks to medical patients or the general public; (2) the risk coefficients for organs and tissues were assumed to be independent of age and gender and applicable to radiation workers only; (3) the number of organs or tissues considered by ICRP in its 1977 recommendations was limited to six, with all other tissues lumped into a category called the remainder; (4) each risk coefficient was represented by a single value (sometimes for acute exposure), selected from a broad range of published values, whereas actual risk coefficients for any given tissue vary by up to factors of 10 or more and depend explicitly on age, gender, dose, dose rate, dose fractionation, and other radiobiological factors (Pochin 1978); and (5) the patient receives medical benefit from diagnostic and therapeutic use of radiation. Quoting directly from ICRP Publication 26 (1977, p.92): “The individual receiving the exposure is himself the direct recipient of the benefit resulting from the procedure. For this reason, it is not appropriate to apply the quantitative values of the Commission’s recommended dose-equivalent limits to medical exposures. With certain medical exposures, a very much higher level of risk may in fact be justified by the benefit derived than by the level judged by the Commission to be appropriate for occupational exposure or for exposure of members of the public.”

The Poston/MIRD Committee position on effective dose was quickly challenged (Thomson et al. 1994; Harding et al. 1994; Clarke 1994; Shield and Lawson 1994). For example, Clarke (1994) and Harding et al. (1994) supported the use of effective dose equivalent for comparing the radiation exposure to a patient from different procedures used in diagnostic

nuclear medicine and in research and to facilitate comparisons between different types of radiological procedures (Harrison and Lopez 2015). Authors continued to calculate effective dose for medical exposures, even though many attributed to effective dose an unwarranted precision (Martin 2007, 2008).

In Publication 103, the ICRP (2007) reiterated that “effective dose is not an individual-specific dose quantity” but rather “the dose to the Reference Person under specified exposure conditions,” and further that “no operational dose quantities have been defined that provide a direct assessment of equivalent dose or effective dose.” In contrast, dose assessments for nuclear medicine patients rely on direct measurements of radionuclides for patient-specific and organ-specific absorbed dose determinations, whereas the standard ICRP calculational approaches for assessing equivalent dose and effective dose for radionuclides in the human “are mainly based on various [indirect radioactivity] measurements and the application of biokinetic models (computational models)” for generalized population groups (ICRP 2007). Although effective dose is used in medical practice as a measure of risk, such use goes beyond its intended purpose (Harrison et al. 2016).

APPROPRIATE USE

The calculated quantity “effective dose” is used appropriately in radiation protection for setting secondary limits for intakes of radionuclides in air and water and for ensuring that exposure limits for radiation workers are not exceeded: “Effective dose is intended for use as a protection quantity. The main uses of effective dose are the prospective dose assessment for planning and optimisation in radiological protection, and demonstration of compliance with dose limits for regulatory purposes” (ICRP 2007, p. 13).

Use of effective dose in radiation protection is attractive because it provides a single-value, risk-associated parameter. According to ICRP Publication 103 (page 75, 2007), effective dose should be used for:

- Prospective dose assessment for planning and optimization in radiological protection (compared to dose limits);
- Establishing a radiation worker’s dose of record;
- Demonstrating compliance with dose limits for regulatory purposes; and
- Comparing typical doses from different diagnostic procedures and similar technologies in medical examinations.

A worker’s dose of record (ICRP 2007) is the effective dose, determined by summing the measured personal dose equivalent $H_p(10)$ and the committed effective dose from intakes of long-lived radionuclides using Reference Person biokinetic parameters. Dose of record is assigned to the worker for purposes of recording, reporting, and demonstrating (retrospectively) compliance with regulatory dose limits. The dose of record assigned to the worker is the computed effective dose received by a Reference Person (not the individual worker) when that anthropomorphic reference model is assumed to be exposed to the same radionuclide intake or external radiation field as the worker. Thus, the workers’ dose of

record is not the actual radiation absorbed dose received by the individual but rather a calculated value based on personnel dosimetry and bioassay to enable reasonable comparisons to regulatory exposure limits.

It follows that effective dose should be applied in radiation protection planning to compare exposures that could result from different work activities. For example, the safety of medical personnel using different procedures associated with diagnostic or therapeutic procedures may be compared using a calculated effective dose. In this context, effective dose might be appropriate for use by institutional review boards and radiation safety committees using reference models and reference biokinetic parameters (ICRP 2007).

Effective dose can be useful in the context of dose optimization in medicine for different groups of medical patients. One might study modifying the approach to performing a certain radiological procedure by examining effective dose for a class of patients, such as adult women. If two approaches to the same procedure lead to similar clinical results, but one reduces substantially the effective dose, then that approach may be considered superior. For example, if it can be shown that performing a radionuclide myocardial perfusion stress imaging test first, and then only performing the rest portion of the study (if the stress images are abnormal) yields similar clinical evaluation of the patient—but with a 50% reduction in the effective dose, then the lower dose procedure may be preferred. However, high uncertainties associated with estimates of effective dose, and thus small changes in effective dose on the order of 10%, are most likely of little consequence.

INAPPROPRIATE USE

In practice, effective dose has been applied incorrectly to predict cancer risk among exposed persons (Harrison and Paquet 2016). The concept of effective dose applies generally to reference models only and not to individual subjects. In its Publication 103 (2007, p. 61), the ICRP acknowledged limitations on use of effective dose and urged caution in its application: “Care is also needed in describing the situations in which effective dose should and should not be used. In some situations, tissue absorbed dose or equivalent dose are more appropriate quantities.”

Since the mathematical formula for calculating effective dose incorporates hypothetical concepts and terms with large uncertainties pertaining to the causal relationships between radiation dose and stochastic effects, its value cannot predict future risk of cancer to any single organ or tissue. Consequently, effective dose cannot predict individual or population cancer risk, and should not be used as the basis for epidemiological studies. The ICRP reiterated this position with its statement in Publication 103 (2007, p. 13): “Effective dose is not recommended for epidemiological evaluations, nor should it be used for detailed specific retrospective investigations of individual exposure and risk.”

Neither equivalent dose nor effective dose should be used for estimating risk of cancer to any specific organ or tissue (ICRP 2007). Since the theoretical and mathematical underpinnings of effective dose are not based on radiobiological correlations between dose and effect for individual organs or tissues, effective dose is not predictive of future cancer

incidence in individuals or population groups. While effective dose and equivalent dose do represent hypothetical constructs of risk, based on long-term follow-up of the Japanese atomic bomb survivors, neither the effective dose nor the equivalent dose are defined by ICRP as predictive measures of individual risk for estimating future incidence of cancer.

Since the tissue weighting factors apply only to stochastic effects, the concept of effective dose is not applicable to short-term radiation damage. By extension, effective dose should never be used to predict risk of detriment from any radiation exposure, internal or external.

Because of overall high uncertainties (ICRP 2007), effective dose should not be used for:

- Retrospective investigations of individual exposure and risk;
- Treatment decisions (such as radionuclide decorporation); and
- Assessing radiation dose to medical patients.

The ICRP also discourages calculation of effective dose to persons or population groups for radiation exposures from natural background sources (ICRP 1991, 2007, 2015).

Since the workers' dose of record is not the actual radiation absorbed dose received by the individual worker and is not predictive of future risk of cancer or any other detrimental effect, it follows that the workers' dose of record should not be used for calculating probability of causation associated with compensation claims.

Effective dose is not applicable to individual medical patients; it cannot predict any short-term, normal-organ radiation damage. Since estimates of cancer risk based on effective dose for an individual could vary by one or two orders of magnitude (Martin 2011), it cannot help physicians explain to patients their risks associated with medical uses of radiation. As ICRP publication 130 (2015, page 30) on medical use of radiopharmaceuticals reiterates, "Effective dose should not be used to assess risks of stochastic effects in retrospective situations for exposures in identified individuals, nor should it be used in epidemiological evaluations of human exposure."

Instead, to assess cancer probability, the patient-specific organ or tissue absorbed dose, not the effective dose, is needed for assessing the probability of cancer induction in exposed individuals (ICRP 2007, p. 76).

Examples of inappropriate use of effective dose

Example 1. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer (Smith-Bindman et al. 2009)—In this paper, Smith-Bindman et al. studied radiation dose associated with 11 common diagnostic CT exams performed on 1,119 adult patients and estimated lifetime attributable risks of cancer by study type from using calculated CT effective doses. The authors determined that 1 of every 270 women (and 1 of every 600 men) who underwent CT coronary angiography at age 40 y will develop cancer from that CT scan.

Use of effective dose is "problematic" when organs and tissues receive only partial exposure or heterogeneous exposure in x-ray diagnostics and computed tomography (ICRP 2007).

Effective dose should not be the quantity used to track individual patient doses for CT medical exams. Preferred alternatives include estimates of organ or tissue absorbed dose based on the computed tomography dose index (CTDI, in units of Gy), and dose-length product (DLP, in units of Gy cm). Effective dose can only be estimated from CTDI or DLP by applying multiple correction and scaling factors with high uncertainties.

Example 2. Absolute risk of excess cancer mortality for medical examinations (Lin 2010)—A common practice involves the multiplication of individual effective dose by the risk factor $5\% \text{ Sv}^{-1}$ to yield a predicted number of future cancer fatalities. In a review of radiation risks from medical imaging procedures, Lin (2000) summarized the mean effective dose for various radiographic procedures, mammography, fluoroscopy, and nuclear medicine, and stated that the “absolute risk of death from cancer with a 1 Sv (1,000 mSv) dose” is 5%. Further, as physician’s advice to patients, Lin (2010) states that effective doses “... are theoretical quantities proposed by the International Commission on Radiation Protection to assess the health risks of low doses of ionizing radiation,” and “It is this author’s opinion that the epidemiological data directly suggest increased cancer risk in the 10 mSv to 100 mSv range, which is relevant to nuclear cardiac and many CT studies” (Lin 2000). Uncertainties in applying risk values of whole body irradiation to the effective dose render these sorts of risk estimates of little value.

Example 3. Dosimetry associated with alpha-particle-emitter-labeled antibody in radionuclide therapy (Sgouros et al. 1999; Jurcic et al. 2002)—Clinical researchers have sometimes multiplied absorbed dose by a quality factor or RBE and have reported organ dose equivalent in units of Sv. Sgouros et al. (1999) and Jurcic et al. (2002) determined the mean energy emitted per nuclear transition for ^{213}Bi and its decay products in liver, spleen, and marrow, “adjusted by a relative biologic effectiveness of 5 for alpha emissions... to yield the absorbed dose equivalent” in Sv and whole-body dose in Gy. The unit sievert infers a tissue weighting factor of 20 for alpha particles and is reserved for stochastic effects for computing effective dose (whole body). Subsequently, the MIRD Committee recognized the need for a well-defined absorbed-dose equivalent formalism with special units applicable to alpha emitters in radionuclide therapy (Sgouros et al. 2009).

IMPORTANCE OF ORGAN ABSORBED DOSE

Absorbed dose is the relevant quantity for evaluating radiation dose to organs and tissues from exposure to external radiation and internal radionuclides in the workplace, the environment, and in medical applications. For example, the absorbed dose in medical patients is properly assessed using patient-specific anatomic geometries and organ mass from CT and biokinetic parameters obtained from direct measurements (such as gamma scintillation imaging systems in nuclear medicine). Absorbed dose and dose rate are also the relevant quantities for external beam radiation therapy treatment planning and for calculating administered activities for radionuclide therapies in nuclear medicine.

Absorbed dose is appropriate for individual subjects (humans or animals), workers, medical patients, and members of the public of any age. When correctly assessed, the organ or tissue absorbed dose correlates with biological effects of radiation, including both short-term

deterministic and long-term stochastic effects. The organ or tissue absorbed dose is also the relevant quantity for evaluating physical radiation dose to organs and tissues from exposure to external radiation and internal radionuclides in the work-place, the environment, and medical facilities. Examples include calculation of tracheobronchial dose from radon and progeny, skin dose and wound dose calculations for skin contaminations and punctures, and patient-specific internal dose from administered radiopharmaceuticals.

SUMMARY

Effective dose has its proper place in radiation protection for comparing occupational exposure against primary standards and for optimizing good radiation safety practices, but not for estimating future cancer incidence. As shown above, effective dose represents a surrogate of risk, developed for establishing and complying with radiation protection standards; it is not a physical quantity. Effective dose presupposes validity of the linear no-threshold dose-response model over all dose ranges (which rarely holds true) and applies only to an age-averaged, gender-averaged (male plus female), region-averaged reference model. The collective weaknesses in all assumptions underpinning calculation of effective dose clearly demonstrate that effective dose is neither numerically nor quantitatively predictive of risk or detriment, prospectively or retrospectively. Consequently, effective dose should not be used to predict individual or population risk of cancer at any dose level. Instead, individual assessments of potential detriment should only be based on organ or tissue radiation absorbed dose together with best scientific understanding of the appropriate absorbed dose- response relationships and risk coefficients derived therefrom.

References

- Brenner DJ. Effective dose: a flawed concept that could and should be replaced. *Brit J Radiol.* 2008; 81:521–523. [PubMed: 18443016]
- Boyd, MA. archived proceedings of the Waste Management Conference (WM2009). Phoenix, Arizona: Mar 1-5. 2009 The confusing world of radiation dosimetry. Available at: <http://www.wmsym.org/archives/2009/pdfs/9444.pdf>(accessed January 4, 2017)
- Clarke SEM. Application of the effective dose equivalent to nuclear medicine patients. *J Nucl Med.* 1994; 35:187. [PubMed: 8271048]
- Harding LK, Elliott AT, Shield RA. Application of the effective dose equivalent to nuclear medicine patients. *J Nucl Med.* 1994; 35:185–186. [PubMed: 8271046]
- Harrison J, Lopez PO. Use of effective dose in medicine. *Annal ICRP.* 2015; 44(1 Suppl):221–222.
- Harrison JD, Paquet F. Overview of ICRP Committee 2: doses from radiation exposure. *Ann ICRP.* 2016; 45:1–8. [PubMed: 27044364]
- Harrison JD, Balonov M, Martin CJ, Ortiz Lopez P, Menzel HG, Simmonds JR, Smith-Bindman R, Wakeford R. Use of effective dose. *Ann ICRP.* 2016; 45(1 Suppl):215–224. [PubMed: 26980800]
- International Commission on Radiation Units and Measurements. Report of the International Commission on Radiation Units and Measurements, ICRU Report 8. Oxford: Oxford University Press; 1957.
- International Commission on Radiation Units and Measurements. Fundamental quantities and units for ionizing radiation. *Journal of the ICRU.* 2011; 11(1)ICRU Report 85a-revised
- International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. Oxford: ICRP; Publication; 1977. p. 26
- International Commission on Radiological Protection. Principles and general procedures for handling emergency and accidental exposures of workers. Oxford: ICRP; Publication; 1978. p. 28

- International Commission on Radiological Protection. 1990 recommendations of the International Commission on Radiological Protection. Oxford: ICRP; Publication; 1991. p. 60
- International Commission on Radiological Protection. The 2007 recommendations of the International Commission on Radiological Protection. Oxford: ICRP; Publication; 2007. p. 103
- International Commission on Radiological Protection. Occupational intakes of radionuclides: part 1. Oxford: ICRP; Publication; 2015. p. 130
- Jurcic JG, Larson SM, Sgouros G, McDevitt MR, Finn RD, Divgi CR, Ballangrud AM, Hamacher KA, Ma D, Humm JL, Brechbiel MW, Molinet R, Scheinberg DA. Targeted α -particle immunotherapy for myeloid leukemia. *Blood*. 2002; 100:1233–1239. [PubMed: 12149203]
- Lin EC. Radiation risk from medical imaging. *Mayo Clin Proc*. 2000; 85:1142–1146.
- Martin CJ. Effective dose: how should it be applied to medical exposure? *Brit J Radiol*. 2007; 80:639–647. [PubMed: 17646189]
- Martin CJ. The application of effective dose to medical exposures. *Radiat Protect Dosim*. 2008; 128:1–4.
- Martin CJ. Effective dose: practice, purpose and pitfalls for nuclear medicine. *Radiol Protect*. 2011; 31:205–219.
- Paquet F, Bailey MR, Leggett RW, Harrison JD. Assessment and interpretation of internal doses: uncertainty and variability. *Ann ICRP*. 2016; 45(Suppl 1):202–214. [PubMed: 27044362]
- Pochin, EE. Why be quantitative about radiation risk estimates? Lauriston S Taylor Lecture Series in Radiation Protection and Measurements. Bethesda, MD: National Council on Radiation Protection and Measurements; 1978.
- Poston JW, MIRD Committee. Application of the effective dose equivalent to nuclear medicine patients. *J Nucl Med*. 1993; 34:714–716. [PubMed: 8455092]
- Sgouros G, Ballangrud AM, Jurcic JG, McDevitt MR, Humm JL, Erdi YE, Mehta BM, Finn RD, Larson SM, Scheinberg DA. Pharmacokinetics and dosimetry of an alpha-particle emitter labeled antibody: ^{213}Bi -HuM195 (anti-CD33) in patients with leukemia. *J Nucl Med*. 1999; 40:1935–1946. [PubMed: 10565792]
- Sgouros G, Howell RW, Bolch WE, Fisher DR. MIRD commentary: proposed name for a dosimetry unit applicable to deterministic biological effects-the barendsen (Bd). *J Nucl Med*. 2009; 50:485–487. [PubMed: 19258259]
- Shield RA, Lawson RS. Use of the effective dose equivalent. *J Nucl Med*. 1994; 35:187–187. [PubMed: 8271048]
- Smith-Bindman R, Lipson J, Marcus R, Kim KP, Mahesh M, Gould R, Berrington de Gonzalez A, Miglioretti DL. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. *Arch Intern Med*. 2009; 169:2078–2086. [PubMed: 20008690]
- Thomson WH, Chandler ST, Griffiths C. Limitations of the effective dose equivalent. *J Nucl Med*. 1994; 35:188–189. [PubMed: 8271049]

Table 1

Weighting factors for effective dose.

Weighting factors for different tissues			
Organs	Tissue weighting factors		
	ICRP26 (1977)	ICRP60 (1990)	ICRP103 (2007)
Gonads	0.25	0.20	0.08
Red Bone Marrow	0.12	0.12	0.12
Colon		0.12	0.12
Lung	0.12	0.12	0.12
Stomach		0.12	0.12
Breasts	0.15	0.05	0.12
Bladder		0.05	0.04
Liver		0.05	0.04
Esophagus		0.05	0.04
Thyroid	0.03	0.05	0.04
Skin		0.01	0.01
Bone surface	0.03	0.01	0.01
Salivary glands			0.01
Brain			0.01
Remainder of body	0.30	0.05	0.12
Total	1.00	1.00	1.00