Radiation Effectiveness Factors for Different Radiation Types

People can be exposed to many different types of ionizing radiation including photons, electrons, alpha particles, and neutrons, and the energies of each radiation type can vary widely. Many studies of the effects of ionizing radiation on a wide variety of biological systems, ranging from simple cells to complex whole organisms, have shown that different types of radiation often differ substantially in their biological effectiveness. That is, the probability that a particular biological response is induced by radiation depends on the radiation type, and sometimes its energy, as well as the absorbed dose. In estimating cancer risks and probability of causation of a cancer (assigned share) in an individual who received known exposures to particular radiation types, it therefore is essential that differences in the biological effectiveness of the different radiations be taken into account.

Differences in biological effectiveness of different radiation types have long been taken into account in radiation protection. The quantity currently used in radiation protection to describe the biological effectiveness of different radiation types is the radiation weighting factor. This factor is used to modify the absorbed dose in an organ or tissue of humans from a given radiation type (the total energy imparted in the organ or tissue divided by its mass), given in Gy, to yield an estimate of equivalent dose, given in Sv. The probability that a cancer (or other stochastic radiation effect) in an irradiated organ or tissue will occur is assumed to be proportional to the equivalent dose, independent of radiation type.

The assigned point values of radiation weighting factors used in radiation protection are based on data on the relative biological effectiveness (RBE) of radiations obtained from radiobiological studies of a variety of responses in different biological systems, as well as judgments about the applicability of estimated RBEs to induction of cancers in humans and theoretical considerations of the relationship between biological effectiveness and the density of ionization produced by different radiations in tissue. The radiation weighting factors currently used in radiation protection include: 1 for photons and electrons of any energy; 20 for alpha particles; and 20 for neutrons of energy 0.1-2 MeV including fission neutrons, 10 for neutrons of energy 10-100 keV or 2-20 MeV, and 5 for neutrons of energy less than 10 keV or greater than 20 MeV. Thus, photons and electrons have a biological effectiveness of 1, by definition, and the radiation weighting factors for the other radiation types represent judgments about their biological effectiveness in humans relative to photons and electrons.

For the purpose of estimating cancer risks and assigned shares in identifiable individuals who received known (estimated) radiation exposures, the term “radiation effectiveness factor,” denoted by REF, has been developed to describe the biological effectiveness of different radiation types (Kocher et al., 2002). There are two reasons why a new term, other than “RBE” or “radiation weighting factor,” is used. First, “RBE” is not appropriate because this quantity strictly applies only to results obtained from specific radiobiological studies and, thus, should not be used to describe an extrapolation of such results to a different biological endpoint, biological system, or condition of exposure. Second, as discussed above, the radiation weighting factor is a

prescribed point quantity, without uncertainty, which is used in radiation protection to calculate equivalent doses, but it is not intended to be used to estimate cancer risks and assigned shares in identifiable individuals who received known exposures. Furthermore, cancer risks and assigned shares are estimated based on estimates of absorbed dose without the need to estimate equivalent doses, and it is essential that uncertainties in the biological effectiveness of different radiation types relative to a defined reference radiation be taken into account.

The radiation effectiveness factor for a particular radiation type is used in estimating cancer risks and assigned shares from actual exposures in accordance with one of the following equations:

Solid tumors –

$$\Re = \mathrm{REF}_{\mathrm{L}} \times \frac{R_{\gamma,\mathrm{H}}}{\mathrm{DDREF}_{\gamma}} \times D \ , \tag{1}$$

$$\Re = \mathrm{REF}_{\mathrm{H}} \times R_{\gamma,\mathrm{H}} \times D \ , \tag{2}$$

Leukemias –

$$\Re = a \times \mathrm{REF}_{\mathrm{L}} \times D \ , \tag{3}$$

$$\Re = a(\mathrm{REF}_{\mathrm{L}} \times D) + b(\mathrm{REF}_{\mathrm{L}} \times D)^2 \ . \tag{4}$$

In these equations –

- $\Re$ is the risk of a particular cancer (i.e., the excess relative risk, ERR) due to exposure to a particular radiation type;
- REF is the radiation effectiveness factor for the radiation type and cancer type of concern;
- the subscripts “L” and “H” denote low doses and dose rates and high doses and dose rates, respectively;
- $R_{(,\mathrm{H}}$ is the risk coefficient (ERR per Gy) at high doses and high dose rates of the reference high-energy gamma (( ) radiation with a defined biological effectiveness of 1, assuming linearity in the dose-response relationships for all solid tumors;
- DDREF is the dose and dose-rate effectiveness factor, which takes into account that the ERR per Gy for solid tumors at low doses and dose rates of photons (and electrons) may be less than the values of $R_{(,\mathrm{H}}$ obtained from studies of exposed populations;
- *a* and *b* are the coefficients of the linear and quadratic terms in a linear-quadratic dose-response relationship which is assumed for leukemias under conditions of acute exposure to high-energy gamma rays; and
- *D* is the estimated absorbed dose from the radiation type of concern.

For most solid tumors, the risk coefficients at high doses and dose rates of high-energy gamma rays, $R_{(,\mathrm{H}}$, are obtained from studies of the Japanese atomic-bomb survivors. The coefficients *a* and *b* in the linear-quadratic dose-response relationship for leukemias under conditions of acute

exposure to high-energy gamma rays also are obtained from studies of the atomic-bomb survivors. The data on leukemias indicate that the two coefficients are approximately equal numerically, and this assumption is used in this work. In the radiation effectiveness factor (REF) for the radiation type of concern, the subscripts L and H denote that this factor is estimated basedon data on RBE at low doses and dose rates or at high doses and dose rates of the reference radiation, respectively.

The equation selected depends on the particular radiation type and cancer of concern. As discussed by Kocher et al. (2002), eq. (1) for solid tumors is used in cases of exposure to photons, electrons, and alpha particles, eq. (2) for solid tumors is used in cases of exposure to neutrons, eq. (3) for leukemias is used in cases of exposure to alpha particles and neutrons and in cases of chronic exposure to photons and electrons, and eq. (4) for leukemias is used in cases of acute exposure to photons and electrons. Not shown in eqs. (1)-(3) is a factor representing an inverse dose-rate effect, which is applied to all exposures to alpha particles and to chronic exposures to neutrons. This factor, which is a multiplier on the right-hand side of these equations, takes into account that the biological effectiveness of high-LET radiations may be higher under conditions of chronic exposure than under conditions of acute exposure. The use of eqs. (1)-(4) is discussed further later in this section.

As noted previously, uncertainties in radiation effectiveness factors for different radiation types are taken into account in estimating cancer risks and assigned shares. These uncertainties are described by means of subjective probability (uncertainty) distributions. The assumed probability distributions are intended to represent judgments about the current state of knowledge of the effectiveness of the different radiation types, relative to high-energy gamma rays, in inducing cancers in humans; they are not intended to represent statistical distributions of results that would be obtained if radiobiological studies of the effectiveness of the different radiations in inducing cancers in humans were performed. The factors representing an inverse dose-rate effect for alpha particles or neutrons under conditions of chronic exposure also are described by subjective probability distributions.

The probability distributions of the radiation effectiveness factors used in this report were developed by Kocher et al. (2002) of *SENES* Oak Ridge under contract with the National Institute of Occupational Safety and Health (NIOSH), and have taken into account peer reviews of the work by NIOSH consultants. The assumed probability distributions of the radiation effectiveness factors for photons and electrons are summarized in Table 1, the distributions for alpha particles are summarized in Table 2, and the distributions for neutrons are summarized in Table 3. For photons and electrons, the probability distributions of the radiation effectiveness factors are applied to all cancers, whereas separate probability distributions are developed for leukemias (including lymphomas and lymphocytic cancers) in cases of exposure to alpha particles and neutrons. The probability distributions of the correction for an inverse dose-rate effect are included in the tables for alpha particles and neutrons.

The procedure for using eqs. (1)-(4) in estimating cancer risks and assigned shares is as follows.

It is assumed that the exposure history of an individual is given in terms of the equivalent dose, in Sv, to the organ or tissue in which a cancer has occurred—i.e., the absorbed dose in that organ or tissue modified by a standard radiation weighting factor, denoted by w_R (formerly called the average quality factor, $\overline{Q}$)—and that the equivalent dose is given for each radiation type (photons, electrons, alpha particles, and neutrons) separately. From the given equivalent dose for a particular radiation type in an organ or tissue (T), denoted by H_T, the absorbed dose (D) in that organ or tissue, in Gy, is calculated as $D_T = H_T/w_R$. The absorbed dose for each radiation type is the quantity that is input to the calculation of cancer risk and assigned share, and each of these absorbed doses is modified by the relevant radiation effectiveness factor in accordance with the appropriate equation.

The treatment of the biological effectiveness of the different radiation types of concern, as represented by the probability distributions of the radiation effectiveness factors summarized in Tables 1-3, differs from the 1985 NIH report in two respects. First, with the exceptions of lung cancer among uranium miners exposed to inhaled radon and its short-lived decay products, with exposure expressed in working level months (WLM), and bone cancer among patients injected with the short-lived alpha emitter ^{224}Ra, the 1985 report considered only radiations for which the biological effectiveness was assumed to be unity (i.e., photons). It was recognized that, at low doses and dose rates, high-energy gamma rays might be less damaging than lower-energy X rays, but the NIH working group did not have sufficient information to make such a distinction. In the present work, the biological effectiveness of all radiation types (photons, electrons, alpha particles, and neutrons) is taken into account for all cancers, with the exception that radon and lung cancer continues to be treated separately based on estimates of exposure in WLM. In particular, a distinction is made between the effectiveness of high-energy gamma rays and lower-energy X rays, as well as low-energy electrons. The second important difference is that uncertainties in the biological effectiveness of all radiation types relative to high-energy gamma rays are now taken into account. Since the 1985 NIH report focused on radiations that were assumed to be equally effective at any energies, there was no need at that time to consider uncertainties in biological effectiveness.

Reference:

Kocher, D.C., Apostoaei, A.I., and Hoffman, F.O. 2002. "Radiation Effectiveness Factors (REFs) for Use in Calculating Probability of Causation of Radiogenic Cancers," report prepared for National Institute of Occupational Safety and Health, SENES Oak Ridge, Inc., Oak Ridge, Tennessee (in preparation).

Table 1. Photons and electrons: Summary of probability distributions of radiation effectiveness factors to be used in estimating cancer risks and assigned shares in accordance with eq. (1), (3), or (4)[a]

Radiation type	Exposure	Probability distribution of radiation effectiveness factor (REF_L)
Photons	Chronic or acute[b]	
E > 250 keV		Single-valued at 1.0 (higher-energy photons are assumed reference radiation)
E = 30-250 keV		Hybrid distribution with – 25% probability assigned to value 1.0; 75% probability assigned to lognormal distribution with 95% confidence interval between 1.0 and 5.0
E < 30 keV		Product of two distributions – (1) hybrid distribution for E = 30-250 keV; and (2) triangular distribution with minimum of 1.0, mode of 1.3, and maximum of 1.6
Electrons	Chronic or acute[b]	
E > 15 keV		Single-valued at 1.0 (assumed to be same as value for reference higher-energy photons)
E < 15 keV[c]		Lognormal distribution with 95% confidence interval between 1.2 and 5.0

[a]Equation (1) applies to solid tumors, eq. (3) applies to leukemias under conditions of chronic exposure, and eq. (4) applies to leukemias under conditions of acute exposure.

[b]When eq. (1) is used, DDREF is always applied under conditions of chronic exposure. At acute doses greater than 0.2 cGy, DDREF is assumed to be 1.0. At acute doses less than 0.2 cGy, a DDREF that can exceed 1.0 is applied, and the distribution of possible values approaches the probability distribution of DDREF that applies to all chronic exposures as the dose approaches zero.

[c]Probability distribution is based on data on RBE for low-energy beta particles emitted in decay of tritium (^3H); distribution is applied to other electrons of energy less than 15 keV, except low-energy Auger electrons emitted by radionuclides that are incorporated into DNA are excluded.

Table 2. Alpha particles: Summary of probability distributions of radiation effectiveness factors to be used in estimating cancer risks and assigned shares in accordance with eq. (1) or (3)[a]

Cancer type	Exposure	Probability distribution of radiation effectiveness factor (REF_L)
Leukemias[b]	Chronic[c]	
All energies of alpha particles		Hybrid distribution with – 25% probability assigned to value 1.0; 50% probability assigned to lognormal distribution with 95% confidence interval between 1.0 and 15; 25% probability assigned to lognormal distribution with 95% confidence interval between 2.0 and 60[d]
Solid tumors	Chronic[c]	
All energies of alpha particles		Lognormal distribution with 95% confidence interval between 3 and 80
Correction for inverse dose-rate effect for all exposures to alpha particles – Discrete distribution with – 70% probability assigned to value 1.0; 20% probability assigned to value 1.5; 7.5% probability assigned to value 2.0; 2.5% probability assigned to value 3.0		

[a]Equation (1) applies to solid tumors, and eq. (3) applies to leukemias.

[b]Assumed probability distribution applies to leukemias, lymphomas, and lymphocytic cancers.

[c]Acute exposures to alpha particles emitted by radionuclides generally should not occur; correction factor to account for inverse dose-rate effect under conditions of chronic exposure to alpha particles is applied in all cases.

[d]Distribution is the same as that assumed for leukemias induced by acute exposure to 0.1-2 MeV neutrons (see Table 3).

Table 3. Neutrons: Summary of probability distributions of radiation effectiveness factors to be used in estimating cancer risks and assigned shares in accordance with eq. (2) or (3)[a]

Cancer type	Exposure	Probability distribution of radiation effectiveness factor (REF_L)
Leukemia[b]	Chronic or acute[c]	
Neutron energies		
E = 0.1-2 MeV[d]		Lognormal distribution with 95% confidence interval between 2.0 and 60
E = 10-100 keV; E = 2-20 MeV		Stepwise uniform distribution with – 30% probability assigned to values from 1.0 to 4.0; 50% probability assigned to values from 4.0 to 8.0; 20% probability assigned to values from 8.0 to 40
E < 10 keV; E > 20 MeV		Stepwise uniform distribution with – 30% probability assigned to values from 1.0 to 2.3; 50% probability assigned to values from 2.3 to 3.5; 20% probability assigned to values from 3.5 to 25

Table is continued on following page.

Table 3. Neutrons: Summary of probability distributions of radiation effectiveness factors (continued)

Cancer type	Exposure	Probability distribution of radiation effectiveness factor (REF_H)
Solid tumors	Chronic or acute[c]	
Neutron energies		
E = 0.1-2 MeV[d]		Lognormal distribution with 95% confidence interval between 2.0 and 30
E = 10-100 keV; E = 2-20 MeV		Stepwise uniform distribution with – 30% probability assigned to values from 1.0 to 3.0; 50% probability assigned to values from 3.0 to 5.0; 20% probability assigned to values from 5.0 to 20
E < 10 keV; E > 20 MeV		Stepwise uniform distribution with – 30% probability assigned to values from 1.0 to 1.6; 50% probability assigned to values from 1.6 to 2.4; 20% probability assigned to values from 2.4 to 12
Correction for inverse dose-rate effect for chronic exposures to neutrons – Discrete distribution with – 50% probability assigned to value 1.0; 30% probability assigned to value 1.5; 15% probability assigned to value 2.0; 5% probability assigned to value 3.0		

[a]Equation (2) applies to solid tumors, and eq. (3) applies to leukemias.
[b]Assumed probability distributions apply to leukemias, lymphomas, and lymphocytic cancers.
[c]Under conditions of chronic exposure only, correction factor to account for inverse dose-rate effect is applied.
[d]Energy range includes spectrum of fission neutrons.