Table 17. Summary of probability distributions of radiation effectiveness factors for electrons to be used in estimating cancer risks and probability of causation in accordance with eq. (14), (15), or (16)[a]

Electron energy	Probability distribution of radiation effectiveness factor (REF_L)
> 15 keV	Single-valued at 1.0 (assumption that such electrons have same biological effectiveness as reference high-energy gamma rays)[b]
< 15 keV[c]	Lognormal distribution having a 95% confidence interval between 1.2 and 5.0

[a]Probability distributions apply to all cancers and at any dose and dose rate.

[b]Based on considerations of the energies of secondary electrons produced by photon interactions in tissue, 15-60 keV electrons should have the same REF_L as 30-250 keV photons (see Table 12). However, a distribution of REF_L greater than unity for 15-60 keV electrons is not adopted in this work, due to the lack of supporting radiobiological data.

[c]Probability distribution of REF_L is based on data on RBE for beta particles emitted in decay of ^3H. Distribution does not apply to Auger-emitting radionuclides that are incorporated into DNA.

SUMMARY OF REFs FOR DIFFERENT RADIATIONS

Based on evaluations of information on the biological effectiveness of various types of ionizing radiation, including neutrons, alpha particles, lower-energy photons, and lower-energy electrons, relative to high-energy photons, we have developed radiation effectiveness factors (REFs) for the different radiation types for use in calculating the probability of causation of specific cancers in humans. The REFs developed in this report are applied to estimates of cancer risk in specific organs or tissues at high acute doses of high-energy gamma rays, which are obtained mainly from studies in the Japanese atomic-bomb survivors.

The REFs developed in this report are expressed as probability distributions. These distributions are intended to represent the current state of knowledge of the biological effectiveness of different radiation types in inducing cancers in humans, taking into account uncertainties in data on relative biological effectiveness (RBE) obtained from relevant radiobiological studies and any other judgments involved in evaluating the available information. The REFs for the different radiations considered in this report are summarized as follows.

Neutrons

The assumed probability distributions of REFs for neutrons are summarized previously in Table 7. Separate distributions of REFs are developed for solid tumors and leukemias. The distributions for solid tumors are REFs that represent data on RBE at high acute doses of the reference high-energy gamma rays, REF_H, whereas the distributions for leukemias are REFs that

represent data on RBE at low doses and low dose rates, REF_L. When REF_H is used to estimate risks of solid tumors at any dose and dose rate of neutrons, a dose and dose-rate effectiveness factor (DDREF) for high-energy gamma rays is not used. REFs at high acute doses of the reference radiation are not used in estimating cancer risks for any other radiation type.

The probability distributions of REF_H for solid tumors and REF_L for leukemias are assumed to depend on neutron energy. Based on the energy dependence of the radiation weighting factor recommended by the ICRP (see Fig. 7), probability distributions of REFs are developed for three groups of energies: 0.1-2 MeV (including fission neutrons), 10-100 keV and 2-20 MeV, and less than 10 keV and greater than 20 MeV.

Under conditions of chronic exposure to neutrons, a small correction representing an inverse dose-rate effect is applied to the probability distributions of REFs for solid tumors and leukemias. This correction is assumed to be independent of neutron energy.

The 50^{th} percentile (median) and the 95% confidence interval (2.5^{th} and 97.5^{th} percentiles) of the assumed probability distributions of REFs for neutrons are given in Tables 18 and 19.

Alpha Particles

The assumed probability distributions of REFs for alpha particles are summarized previously in Table 9. As in the case of neutrons, separate distributions of REFs are developed for solid tumors and leukemias, except the distribution for solid tumors is not applied in estimating risks of lung cancer due to inhalation of radon and its short-lived decay products. The distribution for each cancer type is the REF at low doses and low dose rates of the reference high-energy gamma rays, REF_L. The separate probability distributions of REF_L for solid tumors and leukemias are applied at all energies of alpha particles emitted by radionuclides.

In all cases of exposure to alpha particles emitted by radionuclides, a small correction representing an inverse dose-rate effect under conditions of chronic exposure is applied to the probability distributions of REF_L for solid tumors and leukemias. Acute exposure to alpha particles emitted by radionuclides is assumed not to occur.

The 50^{th} percentile (median) and the 95% confidence interval (2.5^{th} and 97.5^{th} percentiles) of the assumed probability distributions of REF_L for alpha particles are given in Table 20.

Table 18. Summary of 95% confidence intervals of probability distributions of radiation effectiveness factors for neutrons and solid tumors[a]

		95% confidence interval of REF_H[b]		
Neutron energy	Exposure	2.5th percentile	50th percentile	97.5th percentile
0.1-2 MeV[c]	Acute	2.0	7.7	30
	Chronic	2.4	10	47
10-100 keV; 2-20 MeV	Acute	1.2	3.8	18
	Chronic	1.4	4.7	28
< 10 keV; > 20 MeV	Acute	1.1	1.9	11
	Chronic	1.1	2.4	16

[a]Summary description of probability distributions is given in Table 7.
[b]REF_H is radiation effectiveness factor at high acute doses of reference high-energy gamma rays.
[c]REFs for this energy range apply to fission neutrons.

Table 19. Summary of 95% confidence intervals of probability distributions of radiation effectiveness factors for neutrons and leukemias[a]

		95% confidence interval of REF_L[b]		
Neutron energy	Exposure	2.5th percentile	50th percentile	97.5th percentile
0.1-2 MeV[c]	Acute	2.0	11	60
	Chronic	2.5	14	91
10-100 keV; 2-20 MeV	Acute	1.3	5.6	36
	Chronic	1.5	7.1	55
< 10 keV; > 20 MeV	Acute	1.1	2.8	22
	Chronic	1.2	3.4	34

[a]Summary description of probability distributions is given in Table 7.
[b]REF_L is radiation effectiveness factor at low doses and low dose rates of reference high-energy gamma rays.
[c]REFs for this energy range apply to fission neutrons.

Table 20. Summary of 95% confidence intervals of probability distributions of radiation effectiveness factors for alpha particles[a]

		95% confidence interval of REF_L[c]		
Cancer type	Exposure[b]	2.5th percentile	50th percentile	97.5th percentile
Solid tumors	Chronic	3.4	18	101
Leukemias	Chronic	1.0	4.1	42

[a]Summary description of probability distributions is given in Table 9.
[b]All exposures to alpha particles emitted by radionuclides are assumed to be chronic.
[c]REF_L is radiation effectiveness factor at low doses and low dose rates of reference high-energy gamma rays.

Photons

The assumed probability distributions of REFs for photons at low doses and low dose rates, REF_L, are summarized previously in Table 12. The biological effectiveness of photons of energy greater than 250 keV is assumed to be the same as that of high-energy gamma rays, and probability distributions of REF_L greater than unity are applied at energies of 30-250 keV and less than 30 keV. The assumed distributions of REF_L are applied to all cancer types.

The 50th percentile (median) and the 95% confidence interval (2.5th and 97.5th percentiles) of the assumed probability distributions of REF_L for photons are given in Table 21.

Electrons

The assumed probability distributions of REFs for electrons at low doses and low dose rates, REF_L, are summarized previously in Table 17. The biological effectiveness of electrons of energy greater than 15 keV is assumed to be the same as that of high-energy gamma rays, and a probability distribution of REF_L greater than unity is applied at energies less than 15 keV, except Auger-emitting radionuclides that are incorporated into DNA are excluded. The assumed distribution of REF_L at low energies is applied to all cancer types.

The 50th percentile (median) and the 95% confidence interval (2.5th and 97.5th percentiles) of the assumed probability distributions of REF_L for electrons are given in Table 22.

Table 21. Summary of 95% confidence intervals of probability distributions of radiation effectiveness factors for photons[a]

		95% confidence interval of REF_L[b]		
Photon energy	Exposure	2.5th percentile	50th percentile	97.5th percentile
> 250 keV	Acute or chronic	–	1.0	–
30-250 keV	Acute or chronic	1.0	1.9	4.7
< 30 keV	Acute or chronic	1.1	2.4	6.1

[a]Summary description of probability distributions is given in Table 12. Probability distributions of REF_L apply to all cancers.

[b]REF_L is radiation effectiveness factor at low doses and low dose rates of reference high-energy gamma rays.

Table 22. Summary of 95% confidence intervals of probability distributions of radiation effectiveness factors for electrons[a]

		95% confidence interval of REF_L[b]		
Electron energy	Exposure	2.5th percentile	50th percentile	97.5th percentile
> 15 keV	Acute or chronic	–	1.0	–
< 15 keV[c]	Acute or chronic	1.2	2.4	5.0

[a]Summary description of probability distributions is given in Table 17. Probability distributions of REF_L apply to all cancers.

[b]REF_L is radiation effectiveness factor at low doses and low dose rates of reference high-energy gamma rays.

[c]Auger-emitting radionuclides that are incorporated into DNA are excluded. Beta-emitting radionuclides are included if average energy of continuous spectrum of beta particles is less than 15 keV.

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