Table 5. Estimates of RBE_H and RBE_M of fission neutrons for tumor induction in B6CF1 mice derived from analysis of selected study by Edwards (1999)[a]

Tumor	Times of death (days after irradiation)	Sex	RBE_H[b]	RBE_M[b]
Lymphocytic	600-799	Male		6.6 ± 1.8
			2.0 ± 0.3	20 ± 5
			5.7 ± 0.9	12 ± 4
				36 ± 13
		Female	5.4 ± 0.6	8.4 ± 0.7
			11.4 ± 0.6	17.8 ± 1.5
	800-999	Male	2.5 ± 0.5	9.7 ± 1.5
			6.5 ± 1.1	25.2 ± 3.2
		Female	8.5 ± 3.0	8.5 ± 1.8
			17 ± 5	15.8 ± 2.6
Vascular tissue	600-799	Male	4.7 ± 0.6	13.9 ± 2.6
		Female	3.7 ± 1.0	7.2 ± 3.2
	800-999	Male	4.8 ± 1.0	13.7 ± 1.6
		Female	6.4 ± 1.4	8.9 ± 2.0
All epithelial tissue or ovary	600-799	Male	5.5 ± 1.0	23 ± 5
			11.0 ± 1.5	45 ± 7
		Female	10.5 ± 1.5	23 ± 4
	800-999	Male	6.2 ± 1.3	14.4 ± 2.9
			13.4 ± 2.2	31 ± 5
		Female	9.7 ± 1.9	19 ± 6

[a]See Table 5 of Edwards (1999). RBE_H is RBE at high doses and high dose rates of reference high-energy gamma rays, and RBE_M is RBE at low doses and low dose rates obtained by extrapolation of data on dose-response for neutrons and the reference radiation. Analysis was based on data given in Grahn et al. (1992). When two sets of values are given, they represent alternative interpretations that are consistent with the data.

[b]Uncertainties are one standard error.

REF for Fission Neutrons and Solid Tumors

Risks of solid tumors from exposure to neutrons are estimated using eq. (3). The probability distribution of REF_H at high doses and high dose rates of reference high-energy gamma rays is developed based on estimates of RBE_H for solid tumors given in Tables 3-5. The relevant data are those for BALB/c and B6CF1 mice in Table 3, since life-shortening in these mice was due primarily to solid tumors, the various tumors and adenocarcinomas in Table 4, and the non-lymphocytic tumors in Table 5. Based on these data, we assume a lognormal probability distribution of REF_H for fission neutrons and solid tumors having a 95% confidence interval between 2.0 and 30. This distribution, which is shown in Fig. 6, has a geometric mean (median or 50th percentile) and geometric standard deviation of 7.7 and 2.0, respectively. A lognormal distribution was selected based mainly on the variability in estimates of RBE_H and the difficulty in judging a credible upper bound of possible values. Lognormal probability distributions are assumed for several other REFs developed in this report.

Data obtained from studies of tumor induction in other animals are consistent with the probability distribution of REF_H for fission neutrons and solid tumors described above. For example, Wolf et al. (2000) deduced an RBE of about 20-25 for lethal tumors in Sprague-Dawley rats at an acute dose of fission neutrons of 0.1 Gy. In a study in which monkeys were given average doses of 6.7 Gy of *X* rays and 3.4 Gy of fission neutrons, Broerse et al. (1991) derived an RBE for tumor induction of about 4-5. When this RBE is adjusted to account for the difference of about a factor of 2 in the biological effectiveness of *X* rays and gamma rays, as discussed in a later section, an RBE relative to gamma rays of about 8-10 is obtained. Other studies of tumor induction in animals are discussed by the NCRP (1990).

The assumed probability distribution of REF_H for fission neutrons and solid tumors applies to a continuous spectrum of energies that normally ranges from 0.1 to 15 MeV. This spectrum has a most probable energy of 0.8 MeV and an average energy of 2.0 MeV (Shleien et al., 1998). As described later in this section, probability distributions of REFs based on RBEs for fission neutrons are assumed to apply at energies of 0.1-2 MeV.

REF for Fission Neutrons and Leukemias

Risks of leukemias and related diseases, including lymphomas and lymphocytic cancers, from exposure to neutrons are estimated using eq. (2). The probability distribution of REF_L at low doses and low dose rates of reference high-energy gamma rays is developed based on estimates of RBE_M for leukemias given in Tables 3-5. The relevant data are those for RF/Un and RFM mice in Table 3, since life-shortening in these mice was due primarily to leukemias, lymphoma and the various leukemias in Table 4, and lymphocytic tumors in Table 5. Based on these data, we assume a lognormal probability distribution of REF_L for fission neutrons and leukemias having a 95% confidence interval between 2.0 and 60. This distribution has a geometric mean and geometric standard deviation of 11 and 2.4, respectively; it resembles the distribution shown in Fig. 6, except it is more highly skewed toward lower values.

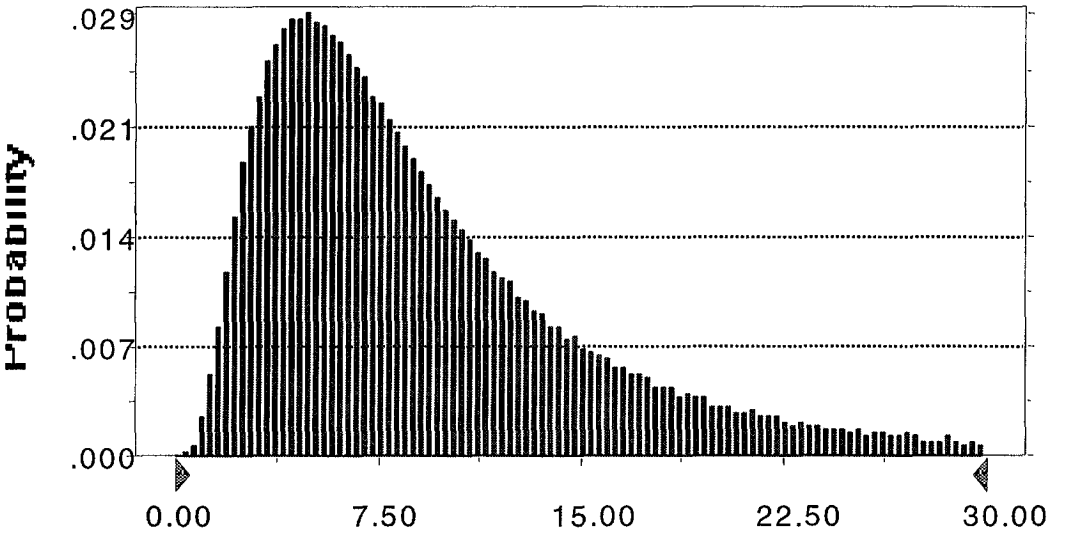

Fig. 6. Assumed lognormal probability distribution of radiation effectiveness factor at high doses and high dose rates of reference high-energy gamma rays, REF_H, for induction of solid tumors by fission neutrons having a 95% confidence interval between 2.0 and 30. Median (50th percentile) of distribution is at 7.7, and 2.5% of values lie beyond 30.

Comparison of REFs for Fission Neutrons with Radiation Protection Quantities

The probability distributions of REFs for fission neutrons described above can be compared with the effective quality factor, $\overline{Q}$, for neutrons of unknown energy recommended by the ICRU (1986) and the radiation weighting factor, w_R, for neutrons of energy 0.1-2 MeV recommended by the ICRP (1991) and the NCRP (1993); see Table 1. The point values of $\overline{Q}$ and w_R are based on estimates of RBE_M and, thus, are directly comparable to the probability distribution of REF_L for leukemias. If we use a $DDREF_\gamma$ of 2 as normally assumed in radiation protection (ICRP, 1991; NCRP, 1993), the probability distribution of REF_H for solid tumors corresponds to a distribution of REF_L having a 95% confidence interval between 4.0 and 60.[15] Therefore, the assumed probability distributions of REFs for fission neutrons encompass the point values of the recommended radiation protection quantities.[16]

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[15]This confidence interval does not represent the range of estimates of RBE_M for fission neutrons obtained from analyses of radiobiological studies, because DDREF for the reference radiation often differed greatly from the value of 2 assumed here. As illustrated in Tables 3-5, upper confidence limits of RBE_M considerably greater than 60 are obtained in some studies (see also Table 2).

[16]The point values $w_R = 20$ and $\overline{Q} = 25$ in Table 1 are at about the 70th and 80th percentiles, respectively, of the inferred probability distribution of REF_L for solid tumors, and are at about the 75th and 85th percentiles of the probability distribution of REF_L for leukemias, respectively.

REFs at Other Neutron Energies

Estimation of cancer risks in humans from exposure to neutrons is complicated by the apparent dependence of RBEs on neutron energy. This energy dependence is represented by the radiation weighting factors currently recommended by the ICRP (1991) and the NCRP (1993) for use in radiation protection (see Table 1 and Fig. 7). In comparison, quality factors at different neutron energies currently used by the U.S. Nuclear Regulatory Commission (NRC, 1991) and the U.S. Department of Energy (DOE, 1993) are given in Table 6. These quality factors were developed by the NCRP (1971) based on calculated depth-dose distributions in a cylindrical phantom or tissue slab at incident neutron energies of 0.025 eV to 400 MeV. The recommended radiation weighting factors and the quality factors used by regulatory authorities in the U.S. indicate that the probability distributions of REFs for fission neutrons described above apply at energies where the biological effectiveness is the highest.

The reductions in the radiation weighting factor by a factor of 2 or 4 at neutron energies outside the range of 0.1-2 MeV recommended by the ICRP (1991) and the NCRP (1993) are based mainly on limited data on the energy dependence of RBE_M obtained from studies in animals and cell cultures, which are reviewed by the NCRP (1990) and the NRPB (Edwards, 1997), and calculations of the energy dependence of the neutron quality factor, such as those shown in Fig. 2 (ICRU, 1986) and given in Table 6 (NCRP, 1971). The variation of RBE_M with neutron energy is illustrated by the data shown in Figs. 8 and 9 (Edwards, 1997; 1999).

The ICRP (1991) also suggested that its recommended step function for the radiation weighting factor given in Table 1 can be represented by a smooth function of the form

$$w_R = 5 + 17\exp[-(\ln(2E))^2/6] \ , \qquad (6)$$

where E is the neutron energy in MeV. This relationship is not intended to imply any biological significance, but it does provide a convenient calculational tool when incident neutron energies are well known. The smooth function in eq. (6) is shown with the recommended step function for the radiation weighting factor in Fig. 7.

As indicated by the data shown in Figs. 8 and 9, experimental information on the energy dependence of RBEs for neutrons is sparse. There are a few studies at energies of 10-100 keV or 2-20 MeV. However, reviews by the NRPB (Edwards, 1997) and the NCRP (1990) did not provide any data on RBEs at energies less than 10 keV or greater than 20 MeV. Thus, based on available data, there is considerable uncertainty in REFs that would represent the biological effectiveness of neutrons in these energy ranges relative to fission neutrons.

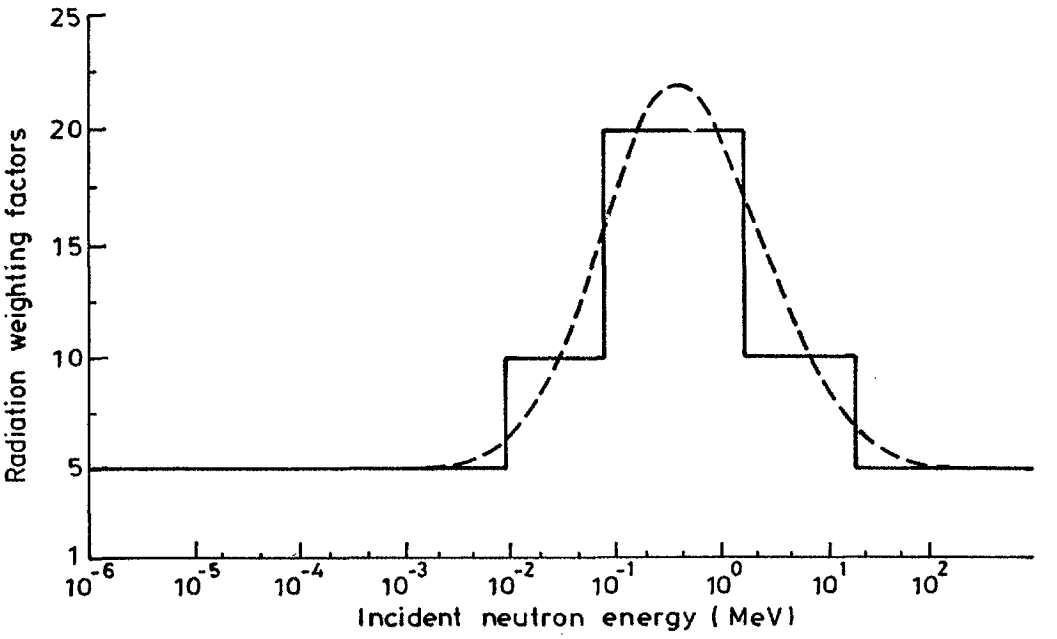

Fig. 7. Radiation weighting factor, w_R, vs. neutron energy given in Fig. A.1 of ICRP (1991). Dashed curve is approximation given by eq. (6).

Table 6. Quality factors for neutrons currently used by U.S. Nuclear Regulatory Commission and U.S. Department of Energy[a]

Neutron energy (MeV)	Mean quality factor	Neutron energy (MeV)	Mean quality quality
≤0.001	2	10	6.5
0.01	2.5	14	7.5
0.1	7.5	20	8
0.5	11	40	7
1	11	60	5.5
2.5	9	100	4
5	8	≥200	3.5
7	7		

[a]Values given in NRC (1991) and DOE (1993) are based on calculations and recommendations by the NCRP (1971).

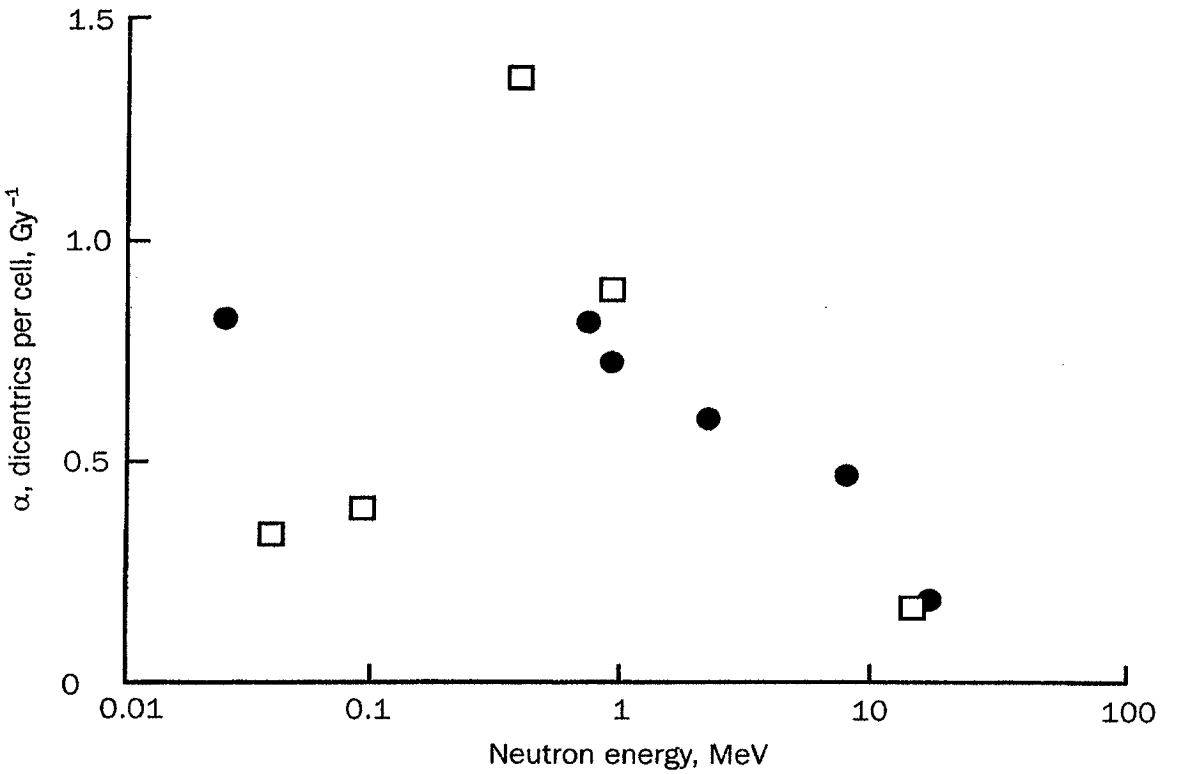

Fig. 8. Variation of RBE_M with neutron energy for induction of dicentric chromosomes in human lymphocytes given in Fig. 6 of Edwards (1997; 1999). Solid circles are data of Edwards et al. (1985; 1990), and open squares are data of Sevan'kaev et al. (1979).

Given the paucity of data on the energy dependence of RBEs for neutrons, we develop subjective probability distributions of REFs for solid tumors and leukemias at energies other than 0.1-2 MeV based on the probability distributions for fission neutrons developed previously and an assumption that the ICRP's step function representation of the radiation weighting factor shown in Fig. 7 provides a general indication of the energy dependence of REFs. We then assume that the probability distributions of REFs for neutrons at energies other than 0.1-2 MeV should have the following three properties:

[1] The lower bound of each distribution should be at 1.0, based on an assumption that neutrons of any energy should not be less effective than high-energy gamma rays in inducing cancers in humans.

[2] The median (50^{th} percentile) of each distribution should be less than the geometric mean of the appropriate lognormal probability distribution for fission neutrons by a factor of about 2 or 4, based on the ICRP's step function representation of the radiation weighting factor (see Table 1 and Fig. 7).

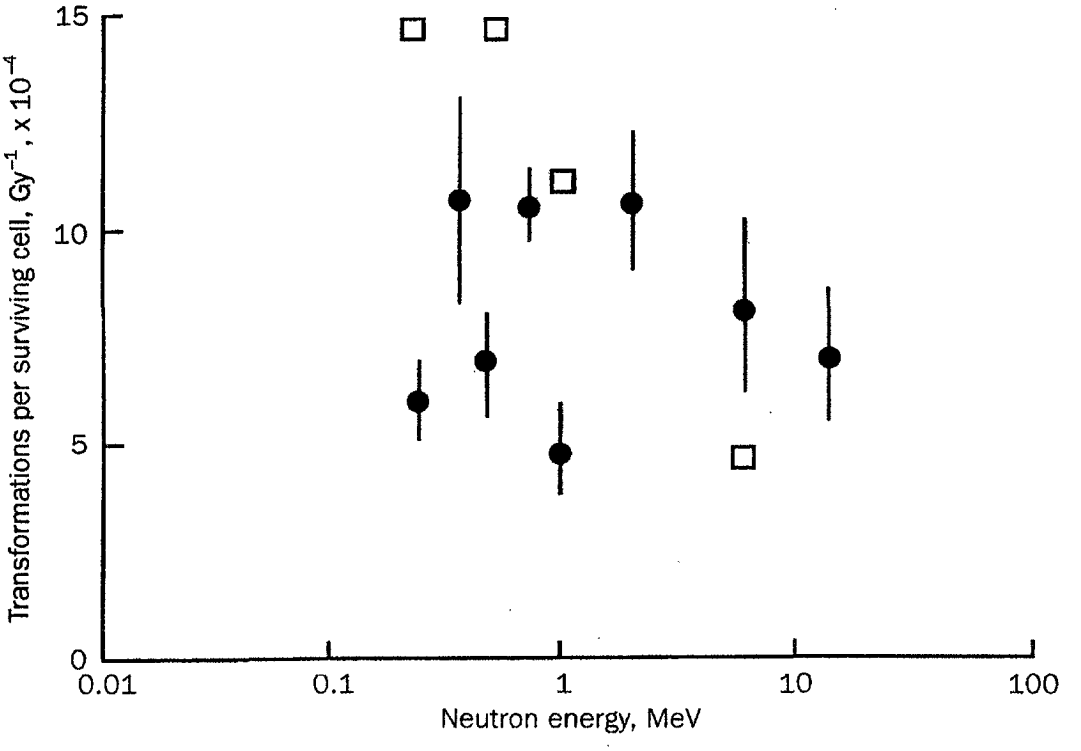

Fig. 9. Variation of RBE_M with neutron energy for transformation of C3H10T½ mouse cells given in Fig. 7 of Edwards (1997). Solid circles are data of Miller et al. (1989), and open squares are data of Coppola (1993); error bars represent one standard error.

[3] The upper 97.5% confidence limit of each distribution should be less than the upper confidence limit of the appropriate distribution for fission neutrons, but by less than a factor of 2 or 4 to take into account that there is substantial uncertainty in the reductions in REFs compared with fission neutrons. Thus, the upper confidence limit relative to the median should increase compared with the ratio of these quantities in the lognormal probability distributions for fission neutrons.

In general, probability distributions of REFs that have these properties must be highly skewed toward values at the low end of an assumed range of values. Only a highly skewed distribution has a fixed lower bound and a decreased median and upper confidence limit but an increased upper confidence limit relative to the median compared with an assumed lognormal distribution for fission neutrons.

There are many probability distributions that can be constructed to represent REFs based on the three properties described above. In the interest of simplicity, we represent the REFs in all

cases by piece-wise uniform (step-function) probability distributions. We assume that each probability distribution has three steps (intervals), and we assign probabilities (weights) of 30% to the first interval, 50% to the second interval, and 20% to the third interval in all cases. The width of each interval in the piece-wise uniform distribution then is adjusted to obtain a distribution in which the median and upper 97.5% confidence limit approximate the desired values. Again, the median is assumed to be about a factor of 2 or 4 less than the median of the appropriate lognormal distribution for fission neutrons, and the reduction in the upper confidence limit is assumed to be less than a factor of 2 or 4. We assume that the upper confidence limit should be reduced by a factor of about 1.7-1.8 when the median is reduced by a factor of 2, and that the reduction should be a factor of $(1.7\text{-}1.8)^2$, or about 3, when the median is reduced by a factor of 4. We believe that reducing the upper confidence limit by a substantially lower factor (e.g., a factor of 1.5 when the median is reduced by a factor of 2) would give too much weight to the uncertainty in the reduction of the median compared with the uncertainty in the appropriate REF for fission neutrons.

The assumed piecewise-uniform probability distributions of REFs for neutrons of energy other than 0.1-2 MeV that have the properties described above are summarized as follows:

E = 10-100 keV or 2-20 MeV (factor of 2 reduction in median) –

Solid tumors (REF_H) –

30% weight to interval from 1.0 to 3.0;
50% weight to interval from 3.0 to 5.0;
20% weight to interval from 5.0 to 20;
Median of 3.8 and upper 97.5% confidence limit of 18.

Leukemias (REF_L) –

30% weight to interval from 1.0 to 4.0;
50% weight to interval from 4.0 to 8.0;
20% weight to interval from 8.0 to 40;
Median of 5.6 and upper 97.5% confidence limit of 36.

E < 10 keV or > 20 MeV (factor of 4 reduction in median) –

Solid tumors (REF_H) –

30% weight to interval from 1.0 to 1.6;
50% weight to interval from 1.6 to 2.4;
20% weight to interval from 2.4 to 12;
Median of 1.9 and upper 97.5% confidence limit of 11.

Leukemias (REF_L) –

30% weight to uniform distribution from 1.0 to 2.3;
50% weight to uniform distribution from 2.3 to 3.5;
20% weight to uniform distribution from 3.5 to 25;
Median of 2.8 and upper 97.5% confidence limit of 22.

The assumed probability distribution of REF_L for leukemias at neutron energies of 10-100 keV or 2-20 MeV is shown in Fig. 10. The distributions in the other cases are similar, the differences being in the assumed widths of each interval in a piece-wise uniform distribution.

The probability distributions of REFs for neutrons of energy other than 0.1-2 MeV described above illustrate the important point discussed in the Introduction that the assumed distributions represent states of knowledge about the biological effectiveness of different radiation types. These distributions are defined by the assumed properties of the lower bound, median, and upper confidence limit and the assumption of a particular form of the distribution (piece-wise uniform), but many other plausible distributions that are consistent with the limited data on RBEs could be developed. The assumed piece-wise uniform distributions clearly do not represent frequency distributions of RBEs that would be obtained if repeated radiobiological experiments were performed, nor are they intended to.

In the piece-wise uniform probability distributions described above, some weight is given to the possibility that the REF for a particular cancer type at energies of 10-100 keV or 2-20 MeV is higher than the corresponding REF for fission neutrons (energies of 0.1-2 MeV), and similarly for the REF for a particular cancer type at energies less than 10 keV or greater than 20 MeV compared with the corresponding REF at 10-100 keV or 2-20 MeV. This possibility is supported by the data shown in Figs. 8 and 9, and by the results of a recent study which indicated that the biological effectiveness of 70-keV and 350-keV neutrons was not significantly different (Miller et al., 2000).

In comparing the assumed probability distributions of REFs for solid tumors and leukemias that apply at particular neutron energies, it is important to bear in mind that the REFs for solid tumors apply at high doses and high dose rates of the reference high-energy gamma rays, whereas the REFs for leukemias apply at low doses and dose rates. Consequently, the probability distribution of REF_L for leukemias at a given energy has higher values than the corresponding distribution of REF_H for solid tumors even though, as noted previously, RBEs for leukemias induced by fission neutrons tend to be lower than RBEs for solid tumors. To provide a better comparison, the assumed distributions of REF_H for solid tumors could be increased by a factor of about 2 to yield equivalent distributions of REF_L, based on the DDREF for the reference radiation generally used in radiation protection (ICRP, 1991; NCRP, 1993).

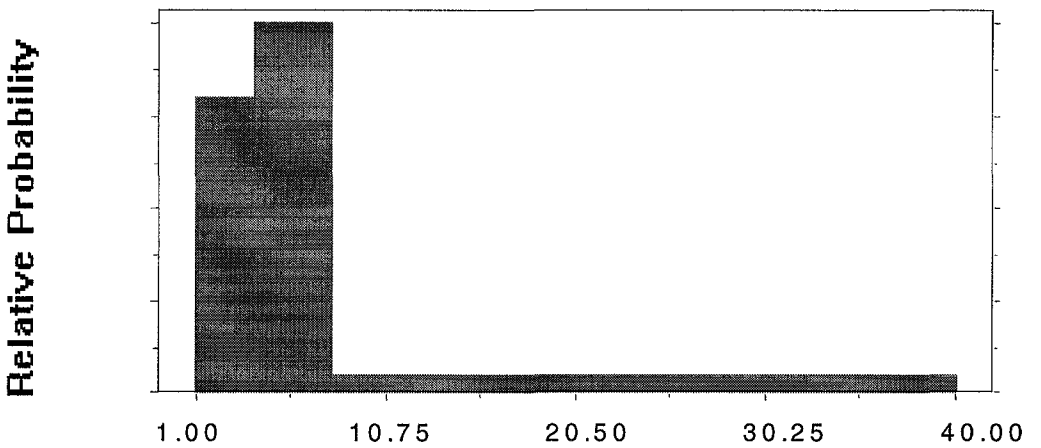

Fig. 10. Assumed piece-wise uniform probability distribution of radiation effectiveness factor at low doses and low dose rates of reference high-energy gamma rays, REF_L, for induction of leukemias by neutrons of energy 10-100 keV or 2-20 MeV. Other probability distributions of REFs for solid tumors and leukemias at neutron energies other than 0.1-2 MeV are similar.

Correction for Inverse Dose-Rate Effect

An additional consideration in estimating cancer risks from exposure to neutrons is the possibility that the biological effectiveness of neutrons and other high-LET radiations increases as the dose rate decreases. This phenomenon is referred to as the inverse dose-rate effect. Some studies of life-shortening and tumor induction in small mammals at relatively high doses of fission neutrons reviewed by the NCRP (1990), the ICRP (1991), and CIRRPC (1995) show an enhancement in biological effectiveness by as much as a factor of about 3 when the same dose is delivered at lower dose rates. However, this effect is not seen in all studies of these endpoints at high doses, and it usually is not seen at lower doses.

Although it is not clear whether the mechanisms responsible for the observed inverse dose-rate effect for fission neutrons in some studies would apply in estimating cancer risks in humans, especially at low doses (CIRRPC, 1995), we apply a small correction to account for this effect. This correction, which we refer to as an enhancement factor, is applied only in cases of chronic exposure to neutrons of any energy; it does not apply to acute exposures.

Based on discussions and summaries of data on life-shortening and tumor induction in mice given in Sections 6 and 8 and Tables 6.2 and 8.2 of NCRP (1990), we assume a probability distribution for the enhancement factor representing an inverse dose-rate effect under conditions of chronic exposure to neutrons that ranges from 1 to 3 and is weighted toward lower values. Specifically, we assume a discrete probability distribution with 50% of the values at 1.0, 30% at 1.5, 15% at 2.0, and 5% at 3.0. The arithmetic mean of this distribution is 1.4. Assigning the

highest weight to the value 1.0 (i.e., an assumption of no inverse dose-rate effect) takes into account that the effect is not seen in all studies at high doses and usually is not seen at low doses of greatest interest in routine exposures of workers and the public.

Applying the assumed probability distribution representing the inverse dose-rate effect to the distributions of REFs shown in Figs. 6 and 10 results in the probability distributions under conditions of chronic exposure to neutrons shown in Figs. 11 and 12.

Summary

At any dose and dose rate of neutrons (n), cancer risks in humans are estimated using the following equations:

Solid tumors –

$$\Re_n = \mathrm{REF}_{n,\mathrm{H}} \times \mathrm{EF}_n \times R_{\gamma,\mathrm{H}} \times D_n \tag{7}$$

Leukemias –

$$\Re_n = a \times \mathrm{REF}_{n,\mathrm{L}} \times \mathrm{EF}_n \times D_n \tag{8}$$

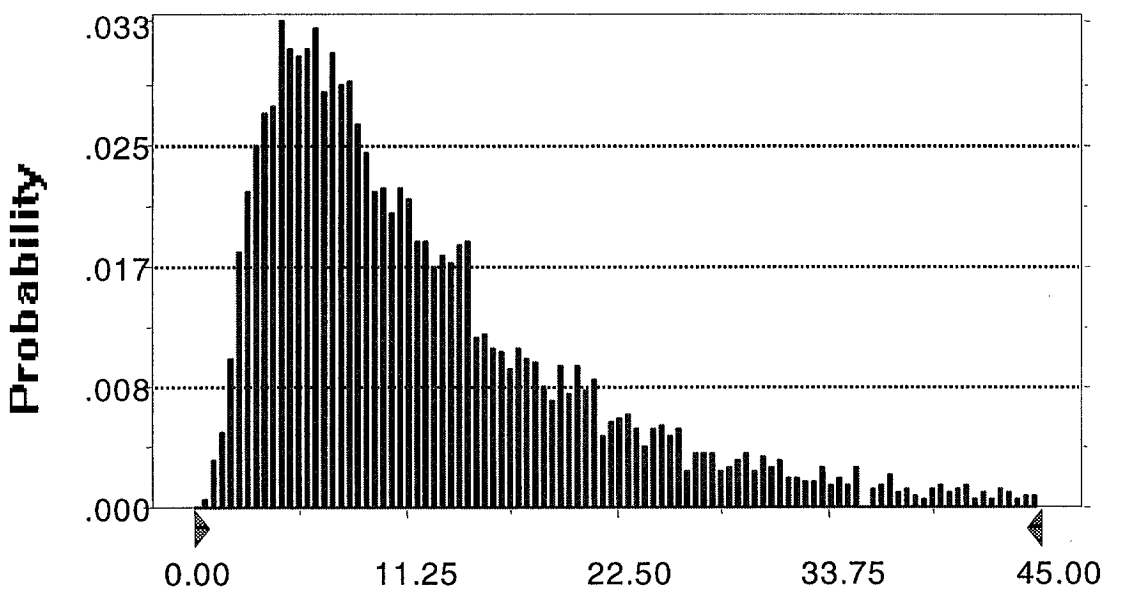

Fig. 11. Assumed probability distribution of $\mathrm{REF_H}$ for fission neutrons and solid tumors shown in Fig. 6 modified by enhancement factor representing inverse dose-rate effect under conditions of chronic exposure. Median of distribution is at 10, and 95% confidence interval lies between 2.4 and 47; about 3% of values lie beyond 45.

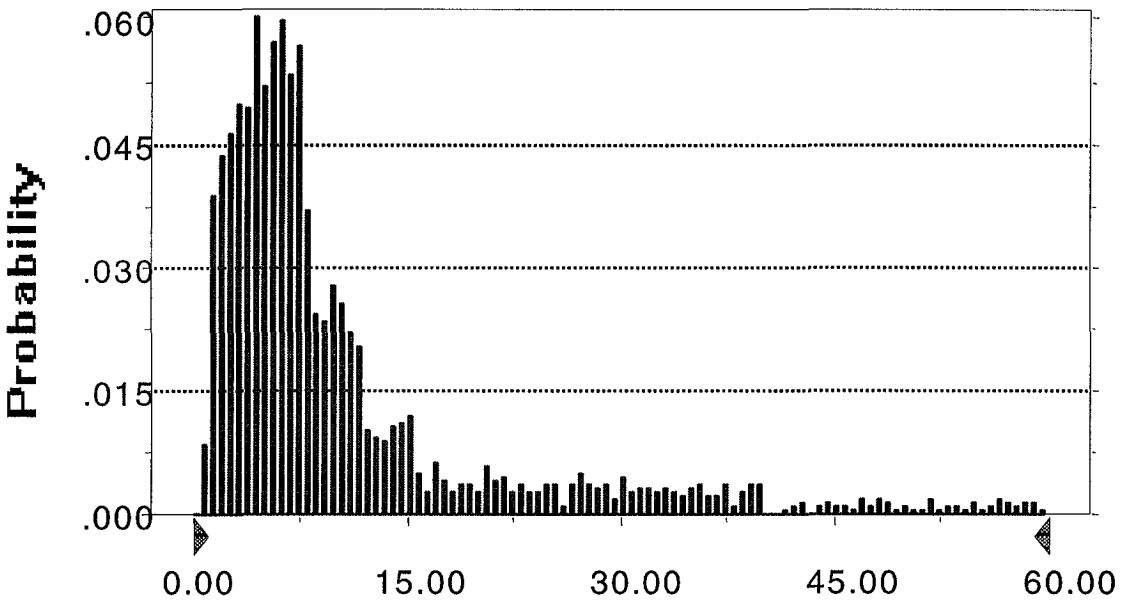

Fig. 12. Assumed probability distribution of REF_L for fission neutrons and leukemias shown in Fig. 10 modified by enhancement factor representing inverse dose-rate effect under conditions of chronic exposure. Median of distribution is at 7, and 95% confidence interval lies between 1.5 and 55; about 1.4% of values lie between 60 and 120.

where $REF_{n,H}$ and $REF_{n,L}$ are the radiation effectiveness factors at high doses and high dose rates and at low doses and dose rates of high-energy gamma rays, respectively, EF_n is the enhancement factor representing an inverse dose-rate effect under conditions of chronic exposure, $R_{\gamma,H}$ is the risk coefficient (ERR per Gy) at high acute doses of high-energy gamma rays for the solid tumor of concern, a is the coefficient of the linear term in the linear-quadratic dose-response relationship for leukemias at high acute doses of high-energy gamma rays, and D_n is the absorbed dose of neutrons in the organ or tissue of concern.

In addition to the distinction between solid tumors and leukemias, which is based on differences in RBEs for the two cancer types as well as the different assumptions about the form of the dose-response relationships at high acute doses of high-energy gamma rays, the REFs for neutrons are assumed to be energy dependent. REFs for five energy ranges are defined, and the energy ranges are those used by the ICRP to define the energy dependence of the radiation weighting factor for neutrons (see Fig. 7). When neutron energies are unknown, the REFs for fission neutrons (0.1-2 MeV) should be used.

The assumed probability distributions of REFs for neutrons and the enhancement factor representing the inverse dose-rate effect under conditions of chronic exposure to neutrons are summarized in Table 7.

Table 7. Summary of probability distributions of radiation effectiveness factors and enhancement factor for neutrons to be used in estimating cancer risks and probability of causation in accordance with eq. (7) or (8)

Cancer type/ Neutron energy	Probability distribution of radiation effectiveness factor (REF)
Solid tumors	
0.1-2 MeV[a]	Lognormal distribution of REF_H having a 95% confidence interval between 2.0 and 30
10-100 keV; 2-20 MeV	Piece-wise uniform distribution of REF_H with – 30% weight to interval from 1.0 to 3.0; 50% weight to interval from 3.0 to 5.0; 20% weight to interval from 5.0 to 20
< 10 keV; > 20 MeV	Piece-wise uniform distribution of REF_H with – 30% weight to interval from 1.0 to 1.6; 50% weight to interval from 1.6 to 2.4; 20% weight to interval from 2.4 to 12
Leukemias	
0.1-2 MeV[a]	Lognormal distribution of REF_L having a 95% confidence interval between 2.0 and 60
10-100 keV; 2-20 MeV	Piece-wise uniform distribution of REF_L with – 30% weight to interval from 1.0 to 4.0; 50% weight to interval from 4.0 to 8.0; 20% weight to interval from 8.0 to 40
< 10 keV; > 20 MeV	Piece-wise uniform distribution of REF_L with – 30% weight to interval from 1.0 to 2.3; 50% weight to interval from 2.3 to 3.5; 20% weight to interval from 3.5 to 25
Enhancement factor representing inverse dose-rate effect under conditions of chronic exposure	
	Discrete distribution with – 50% weight to value 1.0; 30% weight to value 1.5; 15% weight to value 2.0; 5% weight to value 3.0

[a]Energy range also applies to spectrum of fission neutrons. Distributions of REFs at energies of 0.1-2 MeV should be used when neutron energies are unknown.

In the assumed lognormal distributions of REFs for fission neutrons, there is only a small probability of values less than 1.0, and all values in the assumed piece-wise uniform distributions at other neutron energies are greater than 1.0. Thus, the distributions incorporate an assumption that the biological effectiveness of neutrons is greater than that of high-energy gamma rays. Nonetheless, we acknowledge that the REF could be less than 1.0 when most of the dose is delivered by 2.2-MeV gamma rays emitted following capture of thermalized neutrons by ^{1}H nuclei. This situation could occur when the incident neutron energy is less than about 10 keV, but should not be important at higher energies (NCRP, 1971). The possibility of an REF less than 1.0 at low neutron energies is based on the consideration that the biological effectiveness of 2.2-MeV gamma rays could be somewhat less than that of the reference ^{60}Co gamma rays of lower energies (1.2 and 1.3 MeV) used in radiobiological studies to estimate RBEs (Straume, 1995). However, we do not believe that this difference needs to be taken into account in estimating REFs for neutrons. The reduction in the biological effectiveness of 2.2-MeV gamma rays relative to ^{60}Co gamma rays presumably is less than a factor of 2 (Straume, 1995). This difference should be small compared with possible errors in estimating cancer risks that result from an assumption that the spectrum of photons to which the Japanese atomic-bomb survivors were exposed has the same biological effectiveness as ^{60}Co gamma rays. This assumption is implicit in the REFs for neutrons, and other radiations, developed in this report.

We also acknowledge that the assumed probability distributions of REFs for neutrons could tend to overestimate cancer risks in humans at energies greater than about 0.1 MeV (ICRP, 1997). In studies in small mammals used to estimate RBEs for fission neutrons, a substantial fraction of the dose to target tissues was delivered by high-LET radiations (e.g., recoil protons). In humans, however, more of the dose to deep-lying organs and tissues would be delivered by gamma rays produced by neutron interactions in tissue. Therefore, RBEs obtained from studies in small mammals should tend to overestimate the biological effectiveness of incident fission neutrons in many organs and tissues of humans (ICRP, 1997; Edwards, 1997; Edwards, 1999). We have not adjusted the probability distributions of REFs for neutrons to account for possible differences in biological effectiveness in humans compared with small mammals, mainly because calculations indicate that this difference depends in a complicated way on the neutron energy, the target tissue of concern, and the irradiation geometry (ICRP, 1997).

ALPHA PARTICLES

Approach to Estimating RBEs

Like neutrons, alpha particles are high-LET radiations that have been shown to be considerably more effective than low-LET radiations in inducing stochastic responses in biological systems. Alpha particles also are presumed to have linear dose-response relationships for any endpoints at doses below those where significant cell killing occurs. Thus, in principle, it would be desirable to estimate cancer risks in humans exposed to alpha particles based on estimates of RBE at high acute doses of high-energy gamma rays, RBE_H, in accordance with the

model in eq. (3), for example, as we have done for neutrons, to lessen the influence of variations in DDREFs of the reference radiations. The importance of DDREF is indicated by the pronounced increase in RBEs with decreasing dose of alpha particles in the studies summarized in Fig. 13. As is the case with neutrons, high estimates of RBE at low doses, RBE_M, may be due, at least in part, to high values of DDREF for the reference radiation.

As discussed below, however, most studies of the biological effectiveness of alpha particles did not use high acute doses of gamma rays as the reference radiation. Furthermore, an analysis to estimate RBEs of alpha particles at high acute doses of the reference radiation, similar to the analysis for neutrons by Edwards (1997; 1999), has not, to our knowledge, been performed. Such an analysis is not straightforward, due to the dependence of DDREF of the reference radiation on the chosen value of a high dose (see Fig. 5). Therefore, for alpha particles, we developed probability distributions of REFs at low doses and low dose rates of the reference radiation, REF_L, based on estimates of RBE_M obtained from various studies. As is the case with neutrons, the available data for alpha particles indicate that RBEs for leukemias are less than RBEs for solid tumors, and we have developed separate probability distributions of REF_L for solid tumors and leukemias based on RBEs for the two types of cancers.

Alpha particles are somewhat simpler than neutrons in that the range of energies that occur in radioactive decay is limited. A calculation of the energy dependence of the effective quality factor by the ICRU (1986), shown in Fig. 14, indicates that the biological effectiveness of alpha particles is nearly independent of energy over the energy range of concern. Therefore, we have assumed that the probability distributions of REF_L for solid tumors and leukemias can be applied to all alpha particles that occur in radioactive decay.

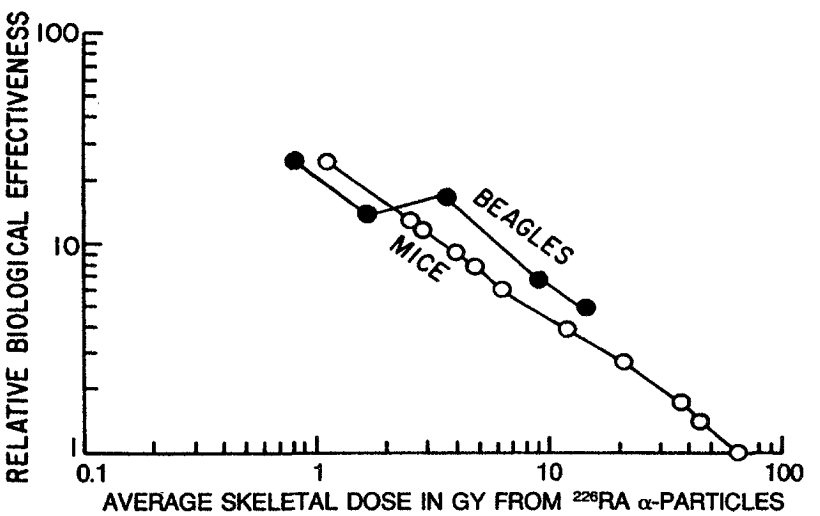

Fig. 13. Biological effectiveness of alpha particles emitted by ^{226}Ra, relative to beta particles emitted by ^{90}Sr and ^{90}Y, for induction of bone tumors in mammals given in Fig. 7.3 of NCRP (1990); curves show pronounced dependence of RBE on dose.