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Author(s): Albrecht M. Kellerer and Linda Walsh

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Solid Cancer Risk Coefficient for Fast Neutrons in Terms of Effective Dose

Albrecht M. Kellerer^{a,b,1} and Linda Walsh^a

^a Radiobiological Institute, University of Munich, Schillerstrasse 42, D-80336 Munich, Germany; and ^b Institute of Radiation Biology, GSF–National Research Center for Environment and Health, Ingolstädter Landstrasse 1, D-85764 Neuherberg, Germany

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Cancer mortality risk coefficients for neutrons have recently been assessed by a procedure that postulates for the neutrons a linear dose dependence, invokes the excess risk of the A-bomb survivors at a γ -ray dose D_1 of 1 Gy, and assumes a neutron RBE as a function of D_1 between 20 and 50. The excess relative risk (ERR) of 0.008/mGy has been obtained for $R_1 = 20$ and 0.016/mGy for $R_1 = 50$. To compare these results to the current ICRP nominal risk coefficient for solid cancer mortality (0.045/Sv for a population of all ages; 0.036/Sv for a working population), the ERR is translated into lifetime attributable risk and is then related to effective dose. The conversion is not trivial, because the neutron effective dose has been defined by ICRP not as a weighted genuine neutron dose (neutron kerma), but as a weighted dose that includes the dose from γ rays that are induced by neutrons in the body. If this is accounted for, the solid cancer mortality risk for a working population is found to agree with the ICRP nominal risk coefficient for neutrons in their most effective energy range, 0.2 MeV to 0.5 MeV. In radiation protection practice, there is an added level of safety, because the effective dose, E , is—for monitoring purposes—assessed in terms of the operational quantity H^* , which overestimates E substantially for neutrons between 0.01 MeV and 2 MeV. © 2002 by Radiation Research Society

INTRODUCTION

Neutron risk estimates are increasingly discussed with regard to issues such as the transport of reactor fuel. Their magnitude has been inferred in the past by multiplying risk coefficients for photon radiation by a low dose limit, $RBE_{\max}$, of the relative biological effectiveness (RBE) of neutrons from cell or animal studies. With regard to solid cancer mortality, estimates of the low-dose excess relative risk (ERR) per gray for γ rays have varied roughly between 0.05 and 0.5 (1), while values of $RBE_{\max}$ from experimental studies lie between 10 and 100 (2). The resulting values of the ERR

per gray for neutrons can thus range from 0.5 to 50, and even values beyond this range have in fact been claimed in the public debates on neutron risk. The preceding paper (3) derived more robust risk estimates for neutrons by postulating—as in the familiar approach—a linear dependence for neutrons, but using otherwise the less uncertain parameters, excess relative risk, ERR_1 , derived from the A-bomb data at an intermediate γ -ray dose, $D_1 = 1$ Gy, and, from animal data, the RBE, R_1 , of neutrons relative to the same γ -ray dose.

Table 1 shows the results from the preceding paper. They have been derived in terms of the common computational tool, i.e. the program AMFIT in the software system EPI-CURE (4), with the RERF data for solid cancer mortality (1950–1990). As in the most recent computations for UNSCEAR (5), the two comparatively simple relative risk models with different time projection are considered: the age-at-exposure model (*e*-model) with modifying factors that depend on age at exposure and gender, and the attained-age model (*a*-model) with modifying factors depending on attained age and gender. The age-at-exposure model provides substantially higher lifetime relative risk for the youngest ages at exposure, but the ERR per unit dose has roughly the same value, whether it is expressed in terms of ERR_{30} (the gender-averaged ERR at 1 Gy for age at exposure 30) for the *e*-model, or in terms of ERR_{60} (the gender-averaged ERR at 1 Gy at age attained 60) for the *a*-model.²

The risk coefficients in columns 2 and 3 are expressed in the appropriate unit, gray. However, it needs to be noted—and this also applies to subsequent figures—that the neutron doses of interest are much smaller, namely 1 Gy/ $R_1 = 20$ mGy to 50 mGy in the analysis that led to Table 1 and fractions of 1 mGy in most radiation protection considerations.

² The earlier paper was not concerned with the age dependence of the risk and it therefore used an average of the numerically similar values ERR_{30} and ERR_{60} . The present analysis requires the lifetime attributable risk, which can depend critically on the projection model. For this reason, Table 1 spells out the separate values. They result from taking the product of the ratio α_n/c_{obs} listed in Table 1 of ref. (3) with the values $ERR_{30} = 0.51/\text{Gy}$ (0.37/Gy – 0.65/Gy) and $ERR_{60} = 0.48/\text{Gy}$ (0.35/Gy – 0.61/Gy) given in ref. (3).

¹ Author to whom correspondence should be addressed at Radiobiological Institute, University of Munich, Schillerstrasse 42, D-80336 Munich; e-mail: amk.sbi@lrz.uni-muenchen.de.

TABLE 1
The Risk Factor for Fast Neutrons in Terms of the
Excess Relative Risk, ERR_{30}/Gy , for the Age-at-
Exposure Model or the ERR_{60}/Gy
for the Attained-Age Model (3)

	Solid cancer mortality (1950–1990)	
	Age-at-exposure model	Attained-age model
R_1	ERR_{30}/Gy	ERR_{60}/Gy
20	8.5 (6.1–10.8)	8.0 (5.8–10.1)
35	13.0 (9.4–16.6)	12.2 (8.9–15.6)
50	16.6 (12.1–21.2)	15.6 (11.4–19.9)

Note. The numbers (and 95% confidence regions) are for the different assumed values of the neutron RBE, R_1 , relative to an acute γ -ray reference dose of 1 Gy.

ICRP (6) specifies the nominal risk coefficient in terms of lifetime attributable risk (LAR) per unit effective dose, E . The risk for solid cancer fatality is presently taken to be 0.045/Sv for a population of all ages and 0.036/Sv for a working population. Being primarily derived from the follow-up of the A-bomb survivors, these numerical values relate essentially to γ rays. However, equal effective doses of different types of radiation are deemed to carry equal risk, and through the choice of the radiation weighting factors, w_R , an implicit risk estimate is thus made for other types of radiation, such as neutrons. To determine whether this implicit risk estimate is consistent with the present risk estimate, the values in Table 1 need to be converted to LAR/Sv.

The transition from excess relative risk to LAR can be made in analogy to the ICRP procedure that led to the nominal risk coefficient. The conversion to effective dose is less straightforward. The neutron excess relative risk per gray relates to the organ-weighted genuine neutron dose, i.e. the absorbed dose from the recoil nuclei released by the neutrons (neutron tissue kerma). In contrast, the neutron effective dose is defined as the product of w_R and the organ-weighted total absorbed dose from neutrons incident on the body, which includes—especially at neutron energies below 1 MeV—a substantial γ -ray dose from neutron capture processes within the body.

The same peculiar convention applies to the organ equivalent doses. The radiation weighting factor must be applied to the sum of the genuine neutron absorbed dose in the organ and the absorbed dose due to γ rays released by the neutrons within the body (6).

CONVERSION FROM EXCESS RELATIVE RISK TO LIFETIME ATTRIBUTABLE RISK

For the conversion into LAR, the ERR needs to be “transported” to a population of all ages with a known distribution of lifetimes and with specified age-dependent solid cancer mortality or incidence rates. The selection of the reference population is, of course, arbitrary. But ICRP has established a precedent in the computations (7) for its

current recommendations (6). These computations derived averages for five reference populations, U.S., UK, Japan, Puerto Rico and China. For comparability to the ICRP risk estimates, the present computations are therefore performed with the same five populations and with the same survival functions and solid cancer mortality rates as used by ICRP.³ The ICRP has employed the simple, unweighted average of the conversion factors for the five populations, and the same procedure is adopted here to derive the conversion factor, f , that links the ERR to the lifetime attributable solid cancer mortality risk, LAR:

$$LAR = f \cdot ERR. \quad (1)$$

As detailed in a separate paper (8), the following conversion factors result for a population of all ages for the age-at-exposure and age-attained models:

$$f = LAR/ERR_{30} = 0.18 \text{ and } LAR/ERR_{60} = 0.12 \quad (2)$$

For occupational exposure, i.e. averaged over ages 25 to 65 at exposure (6), the conversion coefficients are not greatly different for the two projection models:

$$f = LAR/ERR_{30} = 0.11 \text{ and } LAR/ERR_{60} = 0.12 \quad (3)$$

LAR equals the quantity that had previously been termed risk of untimely death (RUD) (9). For low doses, it gives the expected number of excess cancer deaths. It is then equal to the more complicated quantity risk of exposure-induced death (REID) that has been used by UNSCEAR (5). For higher doses, LAR is slightly larger than REID, because it disregards life shortening due to the radiation exposure. In contrast to REID, the quantity LAR increases proportionally to ERR.

Figure 1 gives, as functions of the assumed neutron RBE, R_1 , the risk coefficients LAR/Gy that are obtained with the conversion factors in Eq. (3) from the data in Table 1. The diagram stands for occupational exposure. Since the two projection models provide nearly the same values in this case, their average is plotted. The results are given for assumed values, R_1 , of the neutron RBE that extend beyond the plausible range 20 to 50. This is done to indicate more clearly the dependence on R_1 . The gray band represents the 95% confidence interval in the fit to the data for mortality from solid cancers. As pointed out with regard to Table 1, the appropriate unit of absorbed dose, gray, is used in the notation, but the doses of interest and, accordingly, the values of LAR are much smaller.

Figure 1 is analogous to the diagram that has been given in the preceding article (3) in terms of ERR. As in the earlier diagram, the lower curve and its confidence band represent the inferred reference slope, i.e. the LAR from an acute γ -ray dose of 1 Gy. If a linear dose dependence with no dose and dose-rate effectiveness factor (DDREF) is in-

³ In its most recent report, UNSCEAR has invoked the same five reference populations but has used changed population data and somewhat different concepts, which has increased the risk estimates appreciably [see ref. (5)].

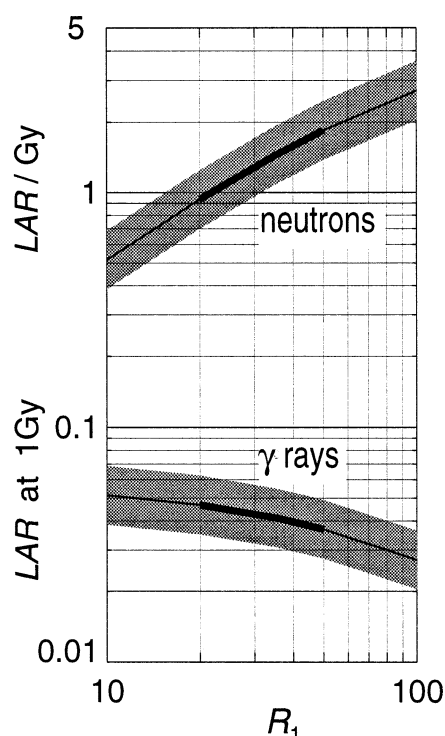


FIG. 1. The risk factor, LAR/Gy, for fast neutrons in terms of the lifetime attributable solid cancer mortality for a working population. The average is given of the nearly equal values for the age-at-exposure and attained-age models. The gray band represents the 95% confidence interval in the fit to the solid cancer mortality data. The values are given in dependence on the value, R_1 , of the assumed neutron RBE relative to a reference γ -ray dose of 1 Gy. The lower curve represents the inferred reference slope, i.e. LAR from an acute γ -ray dose of 1 Gy. For a population of all ages, roughly the same values are obtained in terms of the attained-age model. The age-at-exposure model provides values that are higher by a factor 1.6.

voked, the lower curve represents the γ -ray risk estimate for a working population as inferred from the A-bomb solid cancer mortality data. The γ -ray risk estimate is not the subject of the present study, but it is of interest to note that the result—although it invokes no DDREF—is nevertheless close to the current ICRP risk estimate [LAR/Gy = 0.036/Gy for solid cancer mortality in a working population (6; table S-3)]. A more detailed assessment of the γ -ray risk coefficient (10) substantiates this conclusion.

With the attained-age model, the result for all ages at exposure equals essentially the estimates in Fig. 1 for occupational exposures [see Eqs. (1) and (3)]. However, the age-at-exposure model provides substantially larger values, which reflect the considerably larger risk projection for exposures in childhood. No separate diagram is given for this case, because the values are readily obtained by applying a factor of 1.6.

As stated in the Introduction, one cannot simply multiply the neutron absorbed dose (unit Gy) by the radiation weighting factor, w_R , to obtain the neutron effective dose (unit Sv). This calculation would provide values of the neutron effective dose that are significantly smaller than the

correct values, and it would lead to the conclusion that ICRP has substantially underestimated the neutron risk.

TRANSITION FROM NEUTRON ABSORBED DOSE TO EFFECTIVE DOSE

The Neutron and the γ -Ray Component of the Neutron Effective Dose

Up to this point, reference has been made to the absorbed dose from the charged recoil particles liberated by the neutrons, which is essentially the neutron kerma in the exposed tissue. For the purpose of the present discussion, this is termed the genuine neutron dose. No dose component from γ rays due to neutron capture inside or outside the exposed object—whether a small animal or a human body—is included in this quantity. In experiments with small animals, for example with rodents, the issue of the γ -ray component from neutron capture within the body does not arise, because this contribution is insignificant (11). Depending on the exposure geometry, some γ -ray component is, of course, due to neutron capture *outside* the animal, but in experiments with careful dosimetry, this γ -ray dose is treated separately; i.e., it is not taken to be part of the “neutron absorbed dose”. The situation is different when the human body is exposed to fast neutrons. The γ -dose from neutron capture within the body can be substantial because of the larger dimensions that are involved. This γ -ray component is clearly due to the incident neutron field, but it is a matter of choice whether one defines the “neutron absorbed dose” to include or exclude the γ -ray component. In this paper, the γ -ray component is taken to be excluded, and to avoid confusion the expression genuine neutron dose is used.

In radiobiology and in radiation epidemiology, the γ -ray component is usually not included; i.e., the term neutron absorbed dose refers to the genuine neutron dose. This makes sense, because the γ -ray component can substantially increase the value of the absorbed dose, while it does not add appreciably to the biological effect. The dosimetry for the A-bomb survivors follows the same convention; i.e., the contribution by γ rays from neutron capture within the body is not counted in the neutron dose, but it is included in the total γ -ray dose. In the computations for DS86, the neutron dose is derived in terms of the tissue kerma factors and the local neutron flux spectrum in the organs of interest (12).

In defining the organ equivalent doses and the effective dose for purposes of radiation protection practice, the ICRP has taken a different approach (6). Specifying the energy-dependent radiation weighting factor, w_R , for the external neutron field, ICRP stated that it needs to be applied to the total organ absorbed dose, $D_T = D_{T,\gamma} + D_{T,n}$, that is due to the neutrons incident on the human body. To distinguish D_T from the genuine neutron dose, $D_{T,n}$, for the purpose of the present discussion, D_T will be termed the inclusive neutron dose to the organ. The organ equivalent dose from a

monoenergetic neutron field is then the product of the inclusive neutron dose to the organ and the radiation weighting factor for the neutrons:

$$H_T = w_R D_T = w_R (D_{T,\gamma} + D_{T,n}). \quad (4)$$

The neutron effective dose is obtained by averaging this over the organs in terms of the organ weighting factors, w_T :

$$\begin{aligned} E &= w_R \sum_T w_T D_T \\ &= w_R (\sum_T w_T D_{T,\gamma} + \sum_T w_T D_{T,n}). \end{aligned} \quad (5)$$

It is helpful to write this equation in the simpler form:

$$E = w_R D' = w_R (D'_\gamma + D'_n). \quad (6)$$

w_R is thus a weighting factor for the organ-weighted inclusive neutron dose D' that consists of a sparsely ionizing γ -ray component, D'_γ , and the densely ionizing genuine neutron component, D'_n :

$$\begin{aligned} D'_\gamma &= \sum_T w_T D_{T,\gamma} = \sum_T w_T D_{T,\gamma}, \\ D'_n &= \sum_T w_T D_{T,n}. \end{aligned} \quad (7)$$

Equation (6) sets w_R apart from a neutron RBE which is related to the genuine neutron dose alone. Misconceptions arise when this difference is overlooked.

Let F_n be the fraction of the organ-weighted inclusive neutron dose that is due to the genuine neutron dose:

$$F_n = \sum_T w_T D_{T,n} / \sum_T w_T D_T = D'_n / D'. \quad (8)$$

F_n , as computed by Leuthold *et al.* (13) for an anthropomorphic phantom, is given in Fig. 2 for rotationally symmetrical (ROT) exposure to fast neutrons of the specified energies, E_n (solid line). The neutron fraction decreases rapidly with decreasing neutron energy. Typical moderated neutron fields contribute a major fraction of the dose through neutrons below 1 MeV. The γ -ray component is therefore a substantial part of the inclusive neutron dose.

Rotational symmetry is typical for workplace exposure conditions. For anterior–posterior (AP) exposure, the neutron fraction is somewhat larger (see Fig. 2, dashed line). Dose computations in aviation usually assume isotropic exposure, which gives almost the same result as the rotational geometry. In this paper, we do not address the high neutron energies that are associated with aviation exposures.

NEUTRON RISK COEFFICIENT IN TERMS OF EFFECTIVE DOSE

Formula for the Risk Coefficient

The risk coefficient LAR/Sv in terms of the neutron effective dose is computed by deriving first the inclusive neutron absorbed dose, D' , that corresponds to the neutron effective dose $E = 1$ Sv:

$$D' = (D'_\gamma + D'_n) = E/w_R = 1/w_R \text{ Gy}, \quad (9)$$

with the γ -ray and the neutron components:

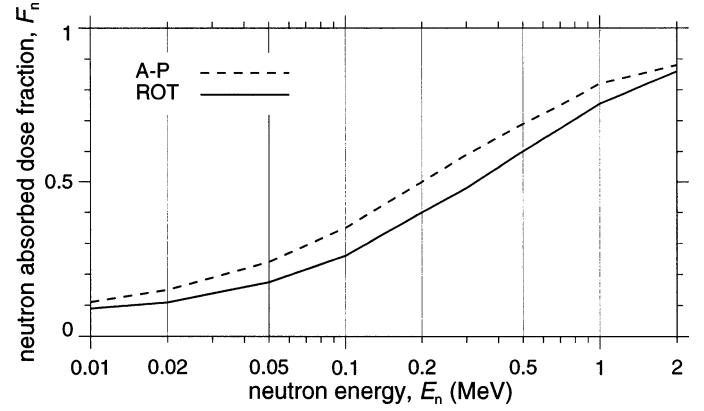


FIG. 2. The fraction, F_n , of the organ-weighted absorbed dose due to neutrons as a function of neutron energy, E_n (13). A-P, anterior–posterior; ROT, rotationally symmetrical.

$$D'_\gamma = (1 - F_n)/w_R \text{ Gy}, \quad D'_n = F_n/w_R \text{ Gy}.$$

The radiation weighting factor, w_R , for neutrons has been specified in terms of a step function in neutron energy, E_n , but ICRP (6) has offered a continuous approximation that is favored in most computations:

$$w_R = 5 + 17 \exp[-\ln(2 E_n)^2/6] \quad (E_n \text{ in MeV}). \quad (10)$$

To facilitate comparison to other computations, this dependence (see dashed line in Fig. 3) is considered here, rather than the step function. As expressed in Eq. (6), w_R is the weighting factor for the inclusive neutron dose, i.e. for the mixture of the γ -ray dose component and the genuine neutron dose.

In a second step, the neutron risk coefficient LAR/Gy from Fig. 1 needs to be applied to the neutron component, while the risk coefficient, c_γ , for photons is to be applied to the γ -ray component:

$$\text{LAR/Sv} = [c_\gamma \cdot (1 - F_n) + (\text{LAR/Gy}) \cdot F_n] \cdot w_R. \quad (11)$$

Since the neutron risk estimate, LAR/Gy, is much larger than the photon risk coefficient, the exact value of c_γ is not very critical. It is therefore an adequate approximation to set c_γ equal to the LAR for photons at 1 Gy (see lower curve in Fig. 1), i.e. the photon risk estimate under the assumption DDREF = 1. This quantity equals the risk coefficient (LAR/Gy) for the neutrons divided by R_1 , and consequently Eq. (11) takes the form:

$$\text{LAR/Sv} = (\text{LAR/Gy}) \cdot [(1 - F_n)/R_1 + F_n]/w_R. \quad (12)$$

Dependence of RBE on Neutron Energy

Up to this point, neutron RBE values, R_1 , have been considered that relate to the energy range, about 0.2 MeV to 0.5 MeV, where neutrons have been shown to have highest efficiency. Dealing with a broader energy range, as in Figs. 2 and 3, one needs to account for the decrease of the RBE at lower and at higher neutron energies.

Experimental studies provide different absolute values of

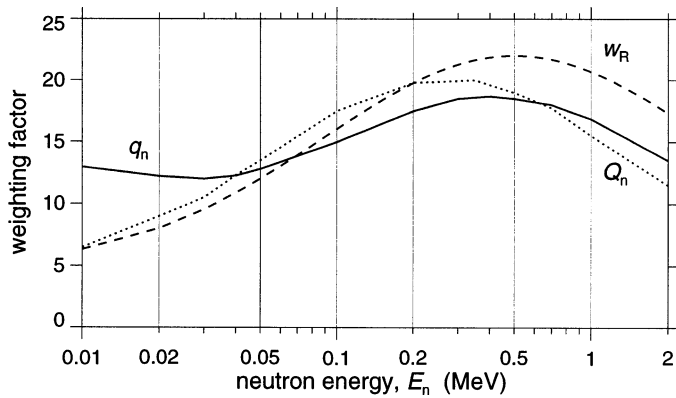


FIG. 3. Radiation weighting factor, w_R (dashed curve) (6), the organ-averaged quality factor, q_n (solid curve), and Q_n (dotted curve) (13) as a function of neutron energy, E_n .

the neutron RBE. However, the majority of results show a consistent energy dependence with a broad maximum, roughly between the neutron energies 0.2 MeV and 0.5 MeV (14–16). The position of the maximum on the energy scale is well explained in terms of microdosimetric data. The essential observation is that neutrons in this energy range tend to release recoil protons just beyond their Bragg peak energies, i.e. protons with maximum LET and with ranges comparable with the cell nucleus.

The general shapes of the dependence of RBE on neutron energy in the assessment of Hall *et al.* (14) and also in the chromosome study of Pandita and Geard (16) are reasonably well in line with the dependence of the quality factor on neutron energy (dotted line in Fig. 3). However, this dependence relates to the exposure of small objects and is not directly applicable to the neutron exposure of the human body, which is large enough to degrade the neutron spectrum appreciably. The solid line in Fig. 3 gives the shallower curve that results from the organ-weighted integration of the quality factor (13); the computations were for an anthropomorphic phantom and for rotational symmetry of the field.⁴ The scaled form of this curve, $q' = q_n(E_n)/q_{n,max}$, is used here as a modifier for R_1 to obtain a plausible neutron energy dependence.

Internal consistency between the quantity effective dose and the operational quantity ambient dose equivalent requires that w_R —since it relates to the mixed γ -ray and neutron dose—be substantially smaller than q_n . Figure 3 shows that this condition is not met. The radiation weighting factor w_R is in fact somewhat larger than q_n at the higher neutron energies, which shows that there is a lack of numerical consistency between the conventions for the radiation weighting factor and the quality factor. This point lies outside the scope of the present study. Nevertheless, in view of the importance of the radiation weighting factor and the quality factor in the current system of radiation protection, the issue is treated briefly in the Appendix.

⁴ q_n is substantially larger at low energies than Q_n , because it accounts for the protons released due to thermal neutron capture by nitrogen.

Numerical Result

Figure 4 gives the coefficient LAR/Sv that results from Eq. (12) with the above assumption on the neutron RBE. As was the case with Fig. 1, the diagram stands for occupational exposure, i.e. for exposure age 25 to 65. Since the two projection models provide almost the same values [see Table 1 and Eq. (3)], their average is plotted. The solid line indicates the value that results with the assumed value $R_1 = 35$. The gray band represents all values that correspond to the values of R_1 between 20 (lower border) and 50 (upper border).

Neutron risks are an issue predominantly with regard to the exposure of adults, e.g. nuclear workers or other persons who handle or guard nuclear fuel. In normal radiation protection practice, i.e. apart from rare accident situations, the neutron risk estimates LAR/Sv for a population of all ages are of comparatively less importance and, as is the case with risk estimates for photons—they are subject to more uncertainty from risk projection into older age. With the attained-age model, the result for all ages at exposure is essentially the same as the estimate for occupational exposures [see Eqs. (2) and (3)]. However, the age-at-exposure model provides substantially larger values, which expresses the considerably larger risk projection in this model for exposures in childhood. As with Fig. 1, no separate diagram is given for this case, because the values are readily obtained by applying a factor of 1.6.

The diagram in Fig. 4 shows that, under the assumption that $R_1 = 35$, there is little disagreement between the current ICRP nominal risk coefficient and the risk coefficients of neutrons that are derived here. At neutron energies below roughly 0.3 MeV, the present estimates lie below the ICRP solid cancer fatality estimate 0.036/Sv for occupational exposure. Above this energy, they exceed the ICRP estimate somewhat. Neutron energies below 0.5 MeV dominate in the moderated neutron fields encountered in occupational

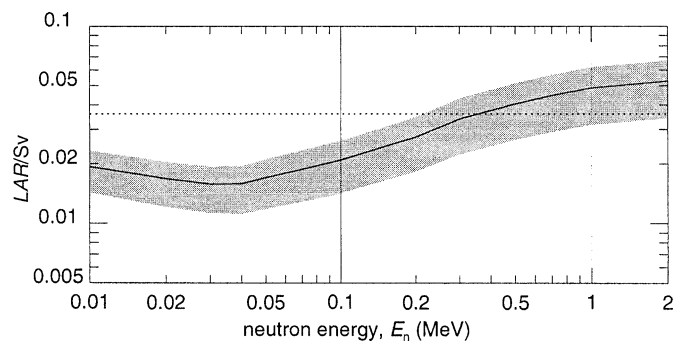


FIG. 4. Lifetime solid cancer mortality risk (LAR/Sv) relative to neutron effective dose for a working population. The values are given in their dependence on neutron energy, E_n . The solid curve results with $R_1 = 35$. The gray band represents the possible values that result for R_1 between 20 and 50. The assumed RBE values between 20 and 50 refer to the energy range 0.2 MeV to 0.5 MeV where the neutrons are most effective; outside this region, the neutron RBE is taken to decrease (see text). The current ICRP nominal risk coefficient for solid cancer mortality (0.036/Sv; working population) is indicated by the dashed line.

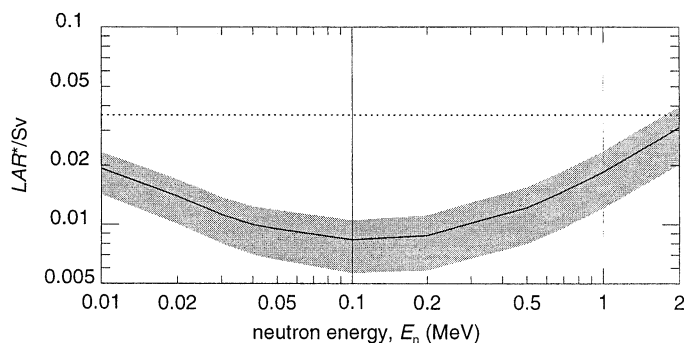


FIG. 5. Lifetime attributable risk (LAR*/Sv), relative to ambient dose equivalent of neutrons (H^*), in its dependence on neutron energy, E_n . The diagram is, apart from the difference between LAR/Sv and LAR*/Sv, analogous to Fig. 4.

radiation protection. In a neutron spectrum outside a transport container for spent nuclear fuel, more than half of the absorbed dose is due to neutrons below energy 0.2 MeV (17).

Risk Coefficient Relative to Ambient Dose Equivalent, H^*

The coefficient LAR/Sv specifies the lifetime attributable solid cancer mortality risk from fast neutrons in relation to the basic ICRP reference quantity effective dose, E . In radiation protection practice, neutron doses are usually estimated and documented in terms of measurements of the ambient dose equivalent, H^* (18), which substitutes as operational quantity for the effective dose. The ratio of H^* to E depends on neutron energy and on the directional distribution of the incident radiation, but in most cases—with the major exception of neutron energies in excess of 40 MeV—the ambient dose equivalent overestimates the effective dose. The risk coefficient, LAR*/Sv, relative to unit ambient dose, H^* , is therefore smaller than LAR/Sv in most cases. Results are given in Fig. 5 for a planar rotationally averaged exposure [(18), p. 98, Fig. 56] which is, as stated before, a realistic assumption for occupational settings.

The results lie safely below the ICRP solid cancer mortality risk coefficient of 0.036/Sv. This confirms that the current radiation weighting factor for neutrons ensures adequate protection from neutron exposures.

CONCLUSION

Solid cancer mortality risk estimates for fast neutrons have been derived in the preceding paper (3) in terms of ERR and absorbed dose. They were based on the A-bomb data on solid cancer mortality data and on assumed values 20 to 50 of the neutron RBE relative to a reference γ -ray dose of 1 Gy. The comparison of the results to the ICRP nominal risk coefficient requires a conversion to lifetime attributable risk and to effective neutron dose, which has been the objective of the present analysis.

For neutron energies from 0.01 MeV to 2 MeV and for occupational exposure, i.e. for exposure ages 25 to 65, the

resulting risk coefficients are found to be largely in line with the ICRP nominal risk coefficient for solid cancer fatality (0.036/Sv). At neutron energies below 0.3 MeV, they are lower than the ICRP risk factor, which reflects the conservative character of the radiation weighting factor, w_R , at low neutron energies.

At neutron energies in excess of 0.2 MeV, risk estimates for all ages at exposure exceed the ICRP estimate 0.045/Sv for solid cancer mortality. They are larger by a factor of 1.6 than the estimates for occupational exposure, or for all ages at exposure under the attained-age model. The increased values reflect the (still insufficiently ascertained) high lifetime risk projection for childhood exposure, which needs to be substantiated in the continuing follow-up of the youngest cohort of A-bomb survivors. When the attained-age model was first suggested (19) as an alternative to the age-at-exposure model, the difference between the two models amounted to a factor of about 2. While the difference in the projection models is about 1.6 [see also ref. (5)] in the present analysis, it is bound to diminish further with the continued follow-up.

The neutron risk coefficients and the related question of the appropriateness of the radiation weighting factor for neutrons are of interest predominantly with regard to occupational radiation exposure. The inherent uncertainties in the risk coefficients and their use as a guideline, rather than a precise yardstick, should preclude any fine tuning of w_R in view of slightly changing risk estimates. However, if the radiation weighting factors for neutrons were to be reconsidered and a better agreement with the quality factor were aimed for, a decrease of w_R at low neutron energies may be advisable (see Appendix). Neutron energies above 2 MeV have not been considered here, and—especially for the much higher neutron energies at aviation altitudes—radiobiological data may be insufficient to allow reliable conclusions.

At the neutron energies that have been considered here, there is a considerable level of conservatism in practice, because the operational quantity ambient dose equivalent, H^* , is commonly used as a substitute for effective dose. H^* tends to overestimate E for fast neutrons, and this is reflected in the fact that the risk coefficients, LAR*/Sv, relative to H^* are consistently smaller than the ICRP nominal risk coefficient.

The present analysis has been restricted to the neutron risk coefficient for cancer mortality excluding leukemia. Leukemia is assumed to contribute only 10% to the total cancer mortality risk (5, 6). Its consideration would therefore be unlikely to change the overall conclusion. In addition, animal studies tend to suggest values of the neutron RBE that are lower, at a specified dose, than the values determined for solid tumors. It is therefore unlikely that the leukemia risk from neutrons exceeds current assumptions.

It is perhaps surprising that the neutron risk coefficients that are derived here do not substantially exceed the ICRP nominal risk coefficient. They might have been expected to

exceed it, because they are not linked to the nominal risk coefficient for photons and are therefore free of the reduction factor $DDREF = 2$. They would also be expected to exceed the current estimate, because RBE values for neutrons are considered that relate to a sizable γ -ray dose of 1 Gy, but are nevertheless fairly high ($R_1 = 20$ to 50). A partial explanation lies in the explicit accounting, in the preceding paper (3), for the contribution of neutrons to the effects observed at an intermediate dose in Hiroshima and Nagasaki. Any increased attribution to neutrons decreases, as had been pointed out earlier (20), the attribution to γ rays, i.e. the γ -ray risk estimate. An increased neutron RBE is therefore less than proportionally reflected in the increased neutron risk estimate. The second and even more important reason is the numerical adjustment for the fact that the effective dose, E , from a neutron exposure includes the substantial γ -ray component that is generated by neutrons in the human body. This particularity of the ICRP definition of effective dose makes the implied weighting factor for the genuine neutron dose substantially larger than the radiation weighting factor w_R (see the Appendix).

The neutron risk coefficient has been derived here in a way that uncouples it from the debatable issue of the dose and dose-rate effectiveness factor (DDREF) for photons. The absolute value of the risk coefficient for neutrons is, in this sense, more fundamental than the radiation weighting factor, which represents the ratio of the two risk coefficients.

APPENDIX

Relationship between w_R and the Quality Factor

All dose-equivalent quantities were defined in terms of the quality factor, $Q(L)$, until ICRP 60 (6) changed this by introducing the radiation weighting factor, w_R , into a new definition of the organ equivalent dose and the effective dose. The quality factor is retained in the definition of the operational quantities ambient dose equivalent and personal dose equivalent (21). The operational quantities are used to verify compliance with the limits for effective dose. In view of this interrelationship, the numerical conventions for w_R and $Q(L)$ are expected to be coherent, but this is currently not the case.

The Implied Radiation Weighting Factor for the Genuine Neutron Dose

w_R is the radiation weighting factor for the inclusive neutron dose, which consists of the genuine neutron dose and the γ -ray dose from neutron interactions in the body. If considered separately, the γ -ray dose needs to be assigned the weighting factor unity and the genuine neutron dose needs to be assigned a weighting factor ω_R that must be chosen so that w_R results for the mixed field.

Using the definition of the neutron fraction F_n [see Eq. (8)], one can rewrite Eq. (6) as a sum of the γ -ray component of the effective neutron dose, which equals D'_γ , and the remaining term that represents the effective dose from the genuine neutron component alone:

$$\begin{aligned} E &= D'_\gamma + (w_R - 1)D'_\gamma + w_R D'_n \\ &= D'_\gamma + [(w_R - 1)/F_n + 1]D'_n. \end{aligned} \quad (A1)$$

This provides the weighting factor for the genuine neutron dose that is implied in the ICRP definition of the neutron effective dose:

$$\omega_R = (w_R - 1)/F_n + 1. \quad (A2)$$

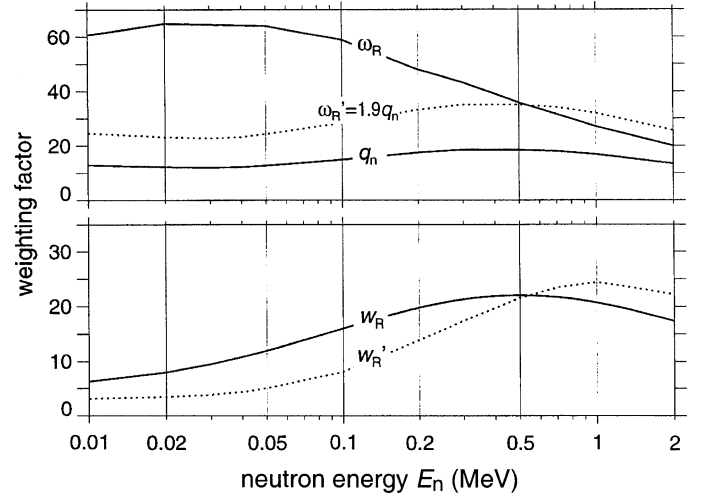


FIG. A1. Upper panel: The implied radiation weighting factor ω_R and the effective quality factor q_n (solid curves) in their dependence on neutron energy, E_n . The dotted curve represents an implied weighting factor ω'_R that corresponds to the potential modification w'_R in the lower panel (dotted line); numerically it equals $1.9 \cdot q_n$. Lower panel: The radiation weighting factor, w_R , for neutrons (solid line) and the modified radiation weighting factor w'_R that would correspond to the dotted line in the upper panel.

The implied weighting factor, ω_R , is represented in the upper panel of Fig. A1 by the upper solid line. It is the parameter that needs to be compared to neutron RBEs observed in experimental studies. ω_R is substantially larger than w_R for neutron energies below 1 MeV, which confirms that w_R —being a weighting factor for a mixed γ and neutron radiation—must not be seen as an RBE value for neutrons. ICRP has emphasized this point consistently, but in the absence of numerical quantification, it may not have been sufficiently appreciated.

The values of the implied weighting factor, ω_R , lie roughly between 50 and 25 in the most effective energy range (0.2 MeV to 1 MeV) of the incident neutrons. This happens to be in fair agreement with the values between 50 to 20 of R_1 that have been assumed in the present analysis on the basis of experiments on tumor induction in rats and in mice with fission neutrons. The further increase of ω_R with decreasing neutron energy makes no sense. It is an artifact of the numerical convention for w_R .

Numerical Interrelationships

The effective quality factor q_n , as given in Fig. 3, is included in the upper panel of Fig. A1 as the lower solid line. It corresponds to the ICRP convention for the quality factor, $Q(L)$ (6). If ICRP had chosen the values of the radiation weighting factor w_R for neutrons to be coherent (for rotational symmetry of the neutron field) with the quality factor, then ω_R would have to be equal to q_n . This is clearly not the case; w_R gives considerably more weight to the neutrons than the quality factor would if it were applied to the genuine neutron dose.

The lack of coherence between w_R and $Q(L)$ is currently compensated by another inconsistency: The application of the quality factor is essentially restricted to its use in the ambient dose equivalent, H^* , and the personal dose equivalent, H_p (10), and these two quantities refer to a depth in the ICRU sphere or in the body of 10 mm (21), which is so shallow that it corresponds to an absorbed dose from the neutron exposure that is considerably larger than the organ-averaged absorbed dose. The low value of the quality factor is thus more than offset by the poor selection of the reference depth, and, accordingly, the ambient neutron dose overestimates the effective neutron dose (18) at neutron energies between 0.1 MeV and 1 MeV.

In the present paper, the neutron RBE has been approximated by the effective quality factor, q_n , rescaled to reach a maximum value R_1 between

20 and 50. The resulting function $R_1 q'$ is inserted with $R_1 = 35$ into the upper panel of Fig. A1 as a dotted line; numerically this curve equals $1.9 \cdot q_n$.

If one intended to give the radiation weighting factor w_R a more meaningful energy dependence w'_R , one might define it so that the corresponding values ω'_R equal $1.9 q_n$, i.e. so that they coincide with the dotted line in the upper panel of Fig. A1. The dotted curve in the lower panel of Fig. A1 gives this modified radiation weighting factor ω'_R . The comparison to the current convention for w_R (solid line) shows that the difference is not large at neutron energies around 0.2 to 2 MeV. For the usual broad energy spectra of neutrons, the differences would tend to cancel in this energy range. At lower energies, the modified convention would decrease the radiation weighting factor considerably.

Analogous considerations would be required to make the quality factor consistent with the radiation weighting factor. But the issue would necessitate a modification of the quantities ambient dose equivalent and personal dose equivalent.

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