Radiation Protection Dosimetry

IMPLEMENTATION OF DOSE-EQUIVALENT METERS BASED ON MICRODOSIMETRIC TECHNIQUES IN RADIATION PROTECTION

Proceedings of a Workshop
held at
Schloß Elmau (FRG)
October 18 – October 20 1988

Organised by:
Commission of the European Communities
Gesellschaft Fuer Strahlen- und Umweltforschung
European Radiation Dosimetry Group (EURADOS)

Proceeding Editors:
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Contents

RADIATION PROTECTION DOSIMETRY is included in **CURRENT CONTENTS**

Radiation Protection Dosimetry
Vol. 29 No. 1/2 pp. 129–134 (1989)
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RADIATION QUALITY AND RADIATION RISKS — SOME CURRENT PROBLEMS

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Abstract — The newly evaluated cancer mortality data of the atomic bomb survivors suggest substantially enhanced risk estimates, and the various factors that are involved in the change are considered. The enhanced risk estimates have already led to added restrictions in the dose limits for radiation workers, and there may be a further tightening of regulations in the future. The impending revision of the quality factors in radiation protection may, therefore, lead to practical difficulties, and a careful consideration of the various aspects involved in a revision is required. A liaison group of ICRU and ICRP has proposed a reformulation of the quality factor that is related not to the LET, but to the microdosimetric variable y. The relation leads to increased quality factors for neutrons, but also to a quality factor for γ rays of only 0.5. Alternatives are here presented that relate the quality factor to LET and that retain γ rays as the reference radiation. One option corresponds to different quality factors for γ rays and X rays, the other option sets the quality factor for photons approximately equal to unity, irrespective of energy.

INTRODUCTION

A workshop on the implementation of novel techniques in radiation protection would be incomplete without an attempt to survey the panorama of current problems and future developments that will influence radiation protection practice. The long awaited but still impending revision of the quality factors has been a topic of several contributions and of extended discussions, and it is inseparable from changes brought about by the new evaluation of the risk coefficients after the reappraisal of the atomic bomb dosimetry. The unresolved questions and the far reaching implications exceed the frame of a short synopsis, but a brief discussion can indicate some of the major problem areas.

Results accumulated through the past – although largely based on indirect evidence from cell studies and animal experiments – have demonstrated a larger effect ratio of low neutron doses to photons than is accounted for by the present ratio of quality factors. NCRP and subsequently ICRP have responded by recommending a selective increase from 10 to 20 of the quality factors for neutrons; but, at least to the physicist, it appeared unattractive to give different weight to heavy charged particles depending on their mode of production. A joint task group of ICRP and ICRU[1] has then proposed a more coherent approach which has three essential features:

(i) Use of a different quality factor for photons of different energies.
(ii) Employment of substantially increased quality factors for densely ionising radiations.
(iii) Linkage of the quality factor to the microdosimetric quantity lineal energy, y, rather than the conventional parameter linear energy density, L.

All three features have precipitated lively discussions. Some of the main issues will be considered subsequently. This will involve not only the problem of the quality factor but also the reassessment of the risk coefficients.

NEW DEVELOPMENTS IN RISK ASSESSMENT

The revision of the atomic bomb dosimetry has led to a new assessment of radiation induced cancer mortality. For solid tumours and for high doses there is surprisingly little influence from the changed dosimetry. One obtains, according to recent reports of RERF[2,3], nearly the same excess relative risk, whether the new or the old dosimetry system is used. There are a number of substantial changes, but taken together they tend to cancel[4]. The situation is different for the bone marrow which, as a relatively shallow organ, is less subject to changes in body penetration by the γ rays; the revision of the dosimetry leads, for leukaemias, to increases of the risk estimates by nearly a factor of 2.

Considerable changes have occurred for added reasons. For solid tumours a proportional enhancement of cancer mortality according to the relative risk model appears to persist. The total number of cases has, therefore, considerably increased since 1975, and this led to a sizable increase of the absolute risk factors. Projection of the relative increases throughout the remaining life times of the exposed persons contributes a further increase. It is also important that substantial data begin to be contributed by those who were exposed

at an early age. For these groups the factors of increase are still insufficiently known, but they appear to be larger than those for the older cohorts.

An indirect but essential change results from the revised dosimetry. The data for cancer mortality are now consistent with linear dose dependences in both cities; but a major role for neutrons is discounted even for Hiroshima. This removes any direct evidence that the dose dependences for γ rays are curvilinear. Accordingly it is now difficult to justify the reduction factor for small doses which has earlier been invoked by ICRP[5] and which has also been considered by UNSCEAR[6].

Figures 1 and 2 show the basic results of the recent evaluations[2,3]. Table 1 gives the new estimates pertaining to large doses and compares them with estimates that were formerly employed.

Larger effects at high doses and the vanishing justification for a reduction factor imply substantially increased risk estimates. This has led to the recommendation of tightened dose limits for radiation workers. In the Federal Republic a lifetime dose limit of 400 mSv has been adopted, in the UK and Sweden an upper bound of 15 mSv has been introduced for the 'annual average' of a worker. Final new conventions will have to await new recommendations by ICRP, but the tendency towards more restricted dose limits will necessitate more accurate dose equivalent determinations in radiation protection practice. It is also evident that any increases of the quality factor can, under these more restrictive conditions, cause difficulties.

PROBLEMS OF THE QUALITY FACTOR

There is no ideal reference parameter for the quality factor. Linear energy density, L, and its distribution are convenient in computations but can not readily be measured. Lineal energy, y, and its distribution can be measured, but require more complicated computations. Unrestricted LET and lineal energy for regions of one micrometre are less closely linked to the effectiveness of a radiation than energy concentrations on the nanometre scale, but these cannot be measured in any practical situation. Harder argues effectively[8], that restricted LET is sufficient to derive any microdosimetric quantity on a nanometre scale. One can similarly state that considerable correlation exists between unrestricted

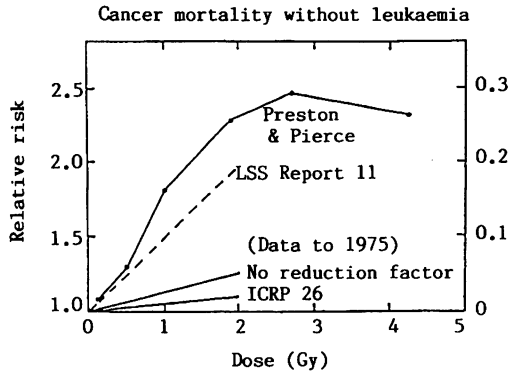

Figure 1. The relative and the absolute risk of cancer mortality (without leukaemia) according to the recent studies of RERF[2,3]. The risk estimates of ICRP[6], and the corresponding data without an assumed reduction factor for low doses are given for comparison. The recent results refer to the entire life-span study sample of atomic bomb survivors. Scaling factors for different age groups are given below. The estimates of ICRP refer to the age distribution of an adult population.

Factors for scaling the results of Preston and Pierce[2] to different age groups.

	Age at radiation exposure (y)		
	<20	20 to 35	>35
Females	2.16	1.29	0.71
Males	0.97	0.58	0.32

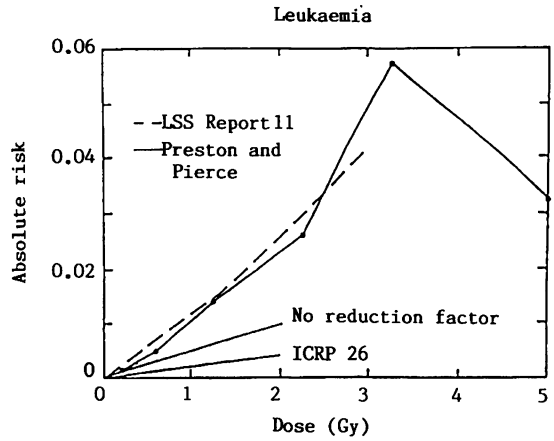

Figure 2. Risk of leukaemia incidence according to the recent studies of RERF[2,3]. The estimates of ICRP[6] and the corresponding data without an assumed reduction factor for low doses are given for comparison. The recent results refer to the entire life-span study sample of atomic bomb survivors; they are derived from the published data[2,3] under the assumption of a mean time at risk of 32 years. Scaling factors for different age groups are given below. The estimates of ICRP refer to the age distribution of an adult population.

Factors for scaling the results of Preston and Pierce[2] to different age groups.

	Age at radiation exposure (y)		
	<20	20 to 35	>35
Females	0.57	0.63	0.88
Males	1.01	1.46	1.45

Table 1. Estimated risk coefficients for radiation-induced cancer mortality. The data are based on recent results from RERF[2,3]. The estimates of UNSCEAR refer to higher doses; the estimates of ICRP contain an assumed reduction factor for small doses and refer to the age distribution of an adult population.

	Additional risk per sievert					
	Solid cancers				Leukaemia	
	Relative		Absolute		Absolute	
New data	F	M	F	M	F	M
Age at exposure						
<20	1.08	0.49	0.19	0.11	0.006	0.01
20 to 35	0.65	0.29	0.12	0.07	0.006	0.014
>35	0.36	0.16	0.06	0.03	0.009	0.015
Average over age and sex	0.5		0.1		0.01	
UNSCEAR (1977)	0.1		0.02		0.004	
ICRP (1977)	0.05		0.01		0.002	

F: females
M: males

LET and lineal energy for larger regions with dimensions of about 1 μm. Hence it has been pointed out that specifications of the quality factor in terms of these quantities are largely interchangeable[9]. There is, therefore, no need for an exclusive choice of the reference parameter, and the subsequent discussions will refer only to LET as reference parameter.

REFORMULATION OF THE ICRU-ICRP PROPOSAL

The proposal of the liaison committee of ICRU and ICRP[1] can be represented by the equation:

$$Q(y) = 0.3\, y\, (1+(y/137)^5)^{-0.4} \qquad (1)$$

which utilises the microdosimetry quantity lineal energy, y (unit, keV.μm^{-1}), for a specified site parameter 1 μm. The equation differs from the formulation in ICRU 40, but is simpler and leads to almost equal numerical values (see Kellerer and Hahn[9]).

Using LET instead of y and choosing γ rays as reference radiation one can employ a different and somewhat simpler relation:

$$Q(L) = \begin{cases} 0.3 + 0.4\, L & \text{for } L<100 \text{ keV.}\mu\text{m}^{-1} \\ 400/\sqrt{L} & \text{otherwise} \end{cases} \qquad (2)$$

The two relations are compared in the two upper panels of Figure 3. The constant value, 0.3, at low values of LET is required, because L disregards energy-loss straggling, i.e. the clustering of energy in individual δ rays, which can cause substantial energy concentrations even at low LET. The influence of these fluctuations is included in the lineal energy, and no correction term is, therefore, required.

Equation 2 assigns the maximum value of the quality factor to an LET of 100 keV.μm^{-1}. This accounts correctly for the high efficiency of intermediate energy neutrons which is largely due to the recoil protons with their maximum LET of 100 keV.μm^{-1}. The most appropriate form of the dependence beyond the break point at L=100 keV.μm^{-1} is less certain. The present convention employs a constant value with no reduction at high values of LET, and this is evidently too conservative. Equation 1 suggests inverse proportionality at high LET which is in line with results from a variety of cell studies. However, some data on heavy-ion-induced animal tumours suggest a less rapid decline of the RBE at high LET[10]. In view of the remaining uncertainty – and also in view of the potentially increasing role of heavy ions in radiation protection – it appears prudent to choose the intermediate formulation as given in Equation 2, i.e. the inverse proportionality to the square root of L.

Figure 3 shows, at low values of y or L, quality factors below unity. But the lowest values do not occur for actual radiation fields which always contain distributions of y or L. The third column in Table 2 lists values which were derived on the basis of Equation 2. The quality factors for neutrons are somewhat larger in absolute value, but relative to γ rays and to X rays they are less enhanced than in the ICRU-ICRP proposal. The value for energetic γ rays is roughly unity if the total degradation spectrum is taken into account, which approximates the condition of a large phantom. It is appropriate to choose high energy γ rays as reference radiation, because γ rays are important in radiation protection and because their effects are the main basis of risk estimates.

The substantially different values of the quality factor for hard γ rays and conventional X rays reflect corresponding differences in observed cellular effects, such as chromosome aberrations[1], for low doses of these radiations. One can, nevertheless, argue that perfect agreement with radiobiological findings is not obligatory and that it introduces unnecessary complications into the practice of radiation protection. On the other hand, it is interesting – and perhaps surprising – to note that different quality factors for photons are not a new feature. They are actually part of the present

convention, although this is not generally appreciated. The first column in Table 2 lists the quality factors which result by integration of the present convention[5] over computed LET spectra for photon radiations (for details Kellerer and Hahn[11]). For photons of 100 keV one obtains a value of about 1.4, regardless of whether the degraded or the undegraded photon spectrum is utilised. If the substantial excess of the values for 100 keV photons over the routinely utilised value of unity has been overlooked or disregarded in the past, it is much less likely that such imprecision will continue to be tolerated when dose limits are markedly reduced.

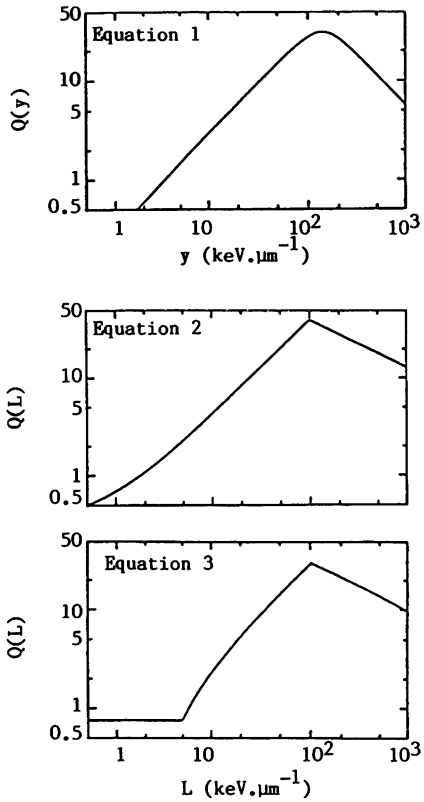

Figure 3. Different options for the definition of the quality factor.

Upper panel: The dependence (see Equation 1) on lineal energy as proposed by a liaison group of ICRU-ICRP[1].

Intermediate panel: Dependence (see Equation 2) on linear energy transfer that results in different quality factors for different photon energies.

Bottom panel: Dependence (see Equation 3) on linear energy transfer that corresponds to a quality factor for photons of approximately 1 for different photon energies.

CHOICE OF A COMMON QUALITY FACTOR FOR PHOTONS

There are, of course, strong arguments for simplicity in radiation protection, and these arguments would favour a constant quality factor Q=1 for photons. Seeking to formulate this condition in terms of LET one finds it impossible without sacrificing the desirable simplicity of the relation for intermediate and higher values of LET. However, the condition can be met approximately by the relation:

$$Q(L) = \begin{cases} 0.75 & \text{for } L < 5 \text{ keV}.\mu\text{m}^{-1} \\ 0.3 \cdot L - 0.75 & \text{other values} \\ 300/\sqrt{L} & \text{for } L > 100 \text{ keV}.\mu\text{m}^{-1} \end{cases} \quad (3)$$

This convention provides the quality factors in the last column of Table 2. The values for photons do not differ by more than 0.2 from unity at any photon energy, so that a conventional value of unity can be employed. For neutrons one obtains the enhanced values which are in line with the ICRU-ICRP proposal.

Equation 3 is represented in the lowest panel of Figure 3. Changing the equation in analogy to Equation 1, we would obtain a smooth function. However, a smooth dependence may actually be

Table 2. Quality factors for photons and neutrons of different energies. The defining relations for the quality factor are identified on the top of the table. Except for the ICRU 40 data, the values refer to the full degradation spectrum. Equations 2 and 3 are evaluated in terms of the LET distributions with a cut-off of 5 keV (for details see Kellerer and Hahn [11]).

	Quality factors			
Photon energy (keV)	Present convention	ICRU 40	Equation 2	Equation 3
50	1.44	1.0	1.98	1.22
100	1.44	1.0	2.05	1.20
200	1.30	0.9	1.68	1.07
500	1.14	0.5	1.19	0.93
1000	1.07	0.5	0.94	0.87
Neutron energy (MeV)				
0.2	12.6	21.8	30.5	21.9
0.4	13.1	23.8	30.9	22.3
1.0	12.4	21.3	27.0	19.4
10.0	6.8	7.3	11.8	8.0

undesirable, because it might generate the erroneous impression of a precisely deduced relation.

If a constant quality factor is used for photons of different energies, one must understand that the value 1 for hard γ rays is a mere matter of convenience and an actual over-estimate. This needs to be accounted for in any consideration of risk estimates. If such estimates are obtained for γ rays, and if X rays are assigned the quality factor 1, one would have to include in the risk estimates the corresponding enhancement factor.

The situation is actually simpler. Risk estimates are based on observations at high doses where there are only minor differences between X rays and γ rays. The estimates can, therefore, be applied to X rays without an enhancement factor. Conversely, there is then less justification for a reduction factor. The new data for the atomic bomb survivors[2,3] appear to be consistent with a linear dose dependence. But for an assumed linear-quadratic dependence the statistical uncertainty would admit a reduction of the slope of about 2 at low doses[2]. However, this reduction would apply only to γ rays, and would be inappropriate for X rays. In adopting a joint quality factor of 1 for photons we should, therefore, utilise the unreduced new estimates.

CONCLUSIONS

The choice of the reference parameter for the quality factor is not a profound issue. There is, of course, no straightforward translation of y spectra into L distributions, and measurements with proportional counters in neutron fields exemplify this fact. An approximate equivalence of definitions can however be achieved, and it is, therefore, sufficient to consider definitions in terms of LET.

Two different options have been formulated in Equations 2 and 3 and this is largely in line with considerations by Dennis[12]. A future tightening of dose limits may necessitate more precision but also less conservatism in radiation protection. Energy dependent quality factors for photons may then be appropriate, and Equation 2 may be a suitable reformulation of the quality factor. Equation 3 is an alternative that corresponds to the indiscriminate use of photons as reference radiation.

The discussion of technical issues is unavoidable. but one must also consider the somewhat deeper question, whether dose limits for workers ought to be linked formally to numerical risk estimates. Such estimates are unavoidably hypothetical and may, therefore, not be commensurable with hard data. Earlier risk estimates[5,6] happened to predict fatalities among radiation workers due to late effects which were about equally infrequent as those acute occupational fatalities reported in other 'safe' professions. To elaborate on this numerical coincidence may have been a temptation that was hard to resist. To promote it to a basic tenet of radiation protection was an error. But the error cannot now be reversed.

More balanced views and more meaningful comparisons will not be achieved by reference to assumed threshold doses for stochastic radiation effects or by invocations of radiation hormesis. But the situation will correct itself through the growing consensus in toxicology that all genotoxic effects lack dose or concentration thresholds. This analogy between ionising radiations and genotoxic chemicals is bound to bring about a more balanced perception of risks, and it will give added importance to principles that have been developed and have long been practised in radiation protection.

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