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RADIATION RESEARCH **114**, 480–488 (1988)

Considerations on a Revision of the Quality Factor

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KELLERER, A. M., AND HAHN, K. Considerations on a Revision of the Quality Factor. *Radiat. Res.* **114**, 480–488 (1988).

A modified analytical expression is proposed for the revised quality factor that has been suggested by a liaison group of ICRP and ICRU. With this modification one obtains, for sparsely ionizing radiation, a quality factor which is proportional to the dose average of lineal energy, y. It is shown that the proposed relation between the quality factor and lineal energy can be translated into a largely equivalent dependence on LET. The choice between the reference parameters LET or y is therefore a secondary problem in an impending revision of the quality factor.

INTRODUCTION

A liaison group of ICRP and ICRU has recently published recommendations which survey radiobiological data relevant to a possible revision of the quality factors for ionizing radiations (*1*). The proposal for a revision of the quality factors addresses two separate issues. The first issue concerns the numerical values of the quality factors. It is recommended to increase the quality factors for densely ionizing radiations, such as neutrons, but also to assign quality factors less than unity to sparsely ionizing radiations, such as γ rays or fast electrons. A second issue concerns the formal definition of the quality factor. It is noted that there are alternatives to the present definition in terms of unrestricted LET, and it is proposed to utilize the microdosimetric variable lineal energy as reference variable.

The report of the joint task group to ICRP and ICRU has helped to focus current discussions. However, it appears that part of the ensuing controversy has been blurred by a failure to separate the two main issues, the problem of the values of the quality factors and that of the formulation of the definition. The subsequent remarks are intended to clarify the matter by addressing the latter aspect separately. A minor but not unessential modification of the defining equation is proposed. Furthermore, and perhaps more importantly, it is suggested that the option between LET as the reference parameter and the microdosimetric variable, y, may not necessitate an exclusive choice. It is instead possible to give equivalent, or nearly equivalent, definitions in terms of the two reference quantities. For most radiation fields encountered in practice it would then be equally admissible to relate the quality factors to LET, for example in computational work, or to utilize the microdosimetric parameters, when quality factors are determined from measurements.

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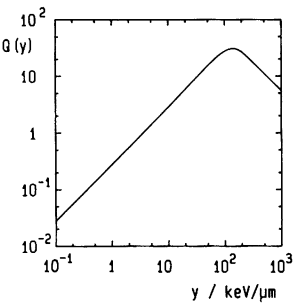

FIG. 1. The proposed redefinition of the quality factor as a function of lineal energy (*1*).

THE PROPOSED RELATION BETWEEN LINEAL ENERGY AND THE QUALITY FACTOR

The document of the joint task group proposes a definition of the quality factor, Q, in terms of the microdosimetric variable lineal energy, y. The main reason for this choice has been that the distribution of lineal energy, but not of LET, can be measured even in an unknown radiation field. In analogy to the current definition of the quality factor in terms of the unrestricted LET, and to ensure the measurability of the distribution, the lineal energy has been related to a spherical region of 1 μm diameter, although it is noted that the effectiveness of a radiation is predominantly determined by energy concentrations over considerably smaller sites. Figure 1 gives the proposed relation between y and the quality factor. The subsequent considerations deal with general characteristics of this relation, rather than the actual values to be used in an impending redefinition of Q.

Both in the proposed modification and in the current definition, the quality factor of a radiation is obtained by an integration over the distribution of the reference variable. In terms of LET one has

$$Q = \int Q(L)d(L)dL, \tag{1}$$

where $d(L)dL$ is the fraction of absorbed dose in the interval L to $L + dL$. The symbol L stands for unrestricted linear energy transfer (*2*). $Q(L)$ is the quality factor as function of linear energy transfer (*3*).

In the proposed redefinition this is replaced by the analogous equation in terms of lineal energy, y,

$$Q = \int Q(y)d(y)dy, \tag{2}$$

where $d(y)dy$ is the fraction of absorbed dose in the interval y to $y + dy$ and $Q(y)$ is the quality factor as function of lineal energy (*1*).

For sparsely ionizing radiation the current definition is trivial; the entire LET distribution can usually be assumed to lie in the range below 3.5 keV/μm which is assigned the value 1. Certain ambiguities in the definition of the distribution of unrestricted LET for electrons have therefore been inconsequential.

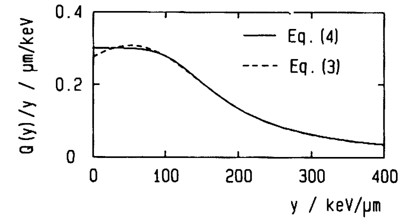

FIG. 2. The ratio of $Q(y)$ and y according to Eq. (3), broken line, and Eq. (4), solid line.

The new definition proposes proportionality of the quality factor to y in the range of small to moderate values. This intended proportionality facilitates measurements and computations. However, it is not adequately represented by the approximation formula in the recent recommendation of the ICRP-ICRU liaison group:

$$Q(y) = 5510/y[1 - \exp(-5 \times 10^{-5}y^2 - 2 \times 10^{-7}y^3)] \qquad (y \text{ in keV}/\mu\text{m}). \qquad (3)$$

The broken line in Fig. 2 indicates the deviation of the relation from linearity at small values of y. Although their magnitude is minor, the deviations would make it impractical to use a dependence such as Eq. (3) in a revised definition of the quality factor. A different analytical expression avoids the difficulty but approximates the dependence in Fig. 1 equally well:

$$Q(y) = 0.3y(1 + (y/137)^5)^{-0.4} \qquad (y \text{ in keV}/\mu\text{m}). \qquad (4)$$

The solid line in Fig. 2 corresponds to this equation. The numerical parameters are in agreement with the proposed relation in Fig. 1, but any numerical changes of the parameters in a future definition need not affect the essential characteristics of the relation. For example, if γ rays rather than conventional X rays will be considered as reference radiation, the parameter 0.3 may be changed to approximately 0.6, and all Q values would be increased accordingly.

Utilizing Eq. (4) one can approximate the quality factor at small and moderate values of y:

$$Q(y) = 0.3y \quad \text{for} \quad y < 40 \qquad (y \text{ in keV}/\mu\text{m}). \qquad (5)$$

Figure 3 gives dose distributions of y for typical radiations. It is apparent that Eq. (5) is an adequate approximation of Eq. (4) for the ranges of values of y that occur with γ rays, X rays, and electrons. For sparsely ionizing radiations one therefore finds

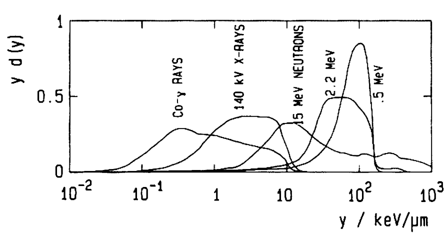

FIG. 3. Dose distributions of lineal energy, y, in a 1-μm sphere for different radiations (7).

that the quality factor is proportional to $\bar{y}_D$, the dose mean lineal energy, i.e., the microdosimetric analog of dose average LET:

$$Q = 0.3 \int y d(y) dy = 0.3 \bar{y}_D \qquad (\bar{y}_D \text{ in keV}/\mu\text{m}). \tag{6}$$

The above relations facilitate the assessment of quality factors according to the revised definition, and they permit straightforward experimental procedures which are based on the variance method (*4, 5*) or its modifications (*6*). It is also convenient that Eq. (6) permits a computation of Q without the need to derive the explicit distribution of y in the sphere; the quantity $\bar{y}_D$ for any reference volume can be obtained directly from the proximity function which characterizes a radiation without regard to a specific geometry (*8, 9*).

As will be seen, one can go a step further and translate the relation between Q and y into a largely equivalent relation between Q and LET.

SUBSTITUTING LET FOR LINEAL ENERGY

Microdosimetry affords more detailed descriptions of energy concentrations in an exposed medium than the treatment in terms of LET. However, such added accuracy is often irrelevant in radiation protection, and, furthermore, the parameter y in a 1-μm sphere need not in itself afford a more detailed description than LET. The proposed choice of y as reference parameter was motivated instead by the reason that y, in contrast to LET, can be measured. In turn, however, LET may be a more suitable reference parameter in simple computations. To use the most convenient concept under varying circumstances, one may therefore wish to establish equivalent definitions of the quality factor. Even if the equivalence is only approximative, it can be adequate under usual conditions.

It is well recognized that energy deposition in a microscopic site cannot in general be determined by a straightforward application of LET. In a first approximation one can equate the energy imparted to the specified site, say of 1 μm diameter, with the product of unrestricted LET and the mean chord length. For nonrelativistic heavy particles of sufficiently long range, this is an adequate approximation. However, considerable deviations occur for sparsely ionizing radiations. Energy-loss straggling can then lead to substantially enhanced energy concentrations. Energy transport by δ rays can have the opposite effect of reducing energy concentration. These limitations of the LET concept need to be noted (*10*), but they do not invalidate the concept, when it is utilized with proper corrections. Harder and co-workers[1] (*11–13*) have made this point and have asserted that even on the basis of the LET concept actual energy concentrations in small volumes can be derived with sufficient accuracy. They were predominantly interested in sites of nanometer dimensions, and accordingly they employed restricted LET with a cutoff $\Delta = 100$ eV. Since our considerations refer to sites of 1 μm diameter, one would have to employ a correspondingly larger cutoff of about 5 keV which is of minor influence for nonrelativistic heavy particles. For the

[1] R. Blohm, Durchgang von Elektronen durch strahlenempfindliche Bereiche des Zellkerns. Thesis, University of Göttingen, 1983.

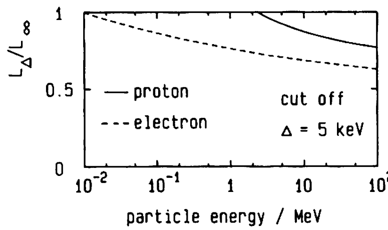

FIG. 4. Ratio of restricted ($\Delta = 5$ keV) to unrestricted collision stopping power for electrons and protons in water. Values computed on the basis of the Bethe formula (see also (*16*), Fig. (3.57)).

purpose of the subsequent considerations it will first be sufficient to utilize unrestricted LET, L. It will then be seen that the use of L is not adequate for electrons where a cutoff is indeed essential, and where a restricted LET, $L_{5\,\mathrm{keV}}$, will therefore be employed.

Consider a charged particle with sufficient energy to lose only a minor fraction in traversing a site of 1 μm diameter. The lineal energy will vary because of different chord lengths, because of energy-loss straggling, and because of changing lateral escape of δ rays (*8*). The combined effect of these factors determines the distribution of y. Computing the distribution may require Monte Carlo simulations, but fairly simple approximations give the weighted average, $\bar{y}_D(L)$, that corresponds to a value L. As has been shown in earlier work (*7, 14*), one has the approximate relation:

$$\bar{y}_D(L) = \frac{9}{8}L + \frac{3\delta}{2d}, \qquad (7)$$

where d is the site diameter and δ is the weighted average of the energy imparted to the site by individual δ rays. The magnitude of δ depends on the velocity of the charged particle and on the site diameter. For electrons of energies in excess of 10 keV—and for protons of at least a few MeV—the maximal δ-ray ranges exceed the assumed site diameter of 1 μm, and δ is then predominantly determined by a geometric cutoff. Microdosimetric computations (*15*) suggest a value of approximately $\delta = 500$ eV for a site of 1 μm diameter, and this corresponds to a δ-ray spectrum with a cutoff at 5 keV (*10*). The approximation of a constant value $\delta = 500$ eV will be employed in the following to demonstrate essential relations.

The factor 9/8 is due to the variations of chord lengths in a sphere. For the purpose of the present approximation, L is equated with unrestricted LET. For a more accurate treatment one would have to use a restricted LET to account for the lateral escape of δ-ray energy, but with the cutoff 5 keV the resulting change would be minor for heavy particles (see Fig. 4). For electrons there is a larger difference between restricted and unrestricted LET, and it will be seen that, for added reasons, a restricted LET needs to be employed.

For particles of low and moderate LET, the dependence of the quality factor on LET can be given in terms of Eqs. (6) and (7)[2]:

[2] To avoid complicated notation, the same symbol is utilized for different functions. $Q(y)$ and $Q(L)$ are distinguished by their different arguments. Whether $Q(L)$ refers to the current definition of the quality factor or to the proposed revision is evident from the context.

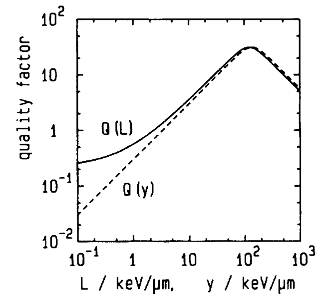

FIG. 5. Comparison of the proposed quality factor as a function of LET, L, solid line, or lineal energy, y, broken line.

$$Q(L) = 0.3\bar{y}_D(L)$$
$$= 0.3\left(\frac{9}{8}L + \frac{3\delta}{2d}\right) = 0.34L + 0.22 \qquad (y,\ L,\ \text{and}\ \delta/d\ \text{in keV}/\mu\text{m}). \qquad (8)$$

For a radiation field with a range of low to moderate LET values one needs to integrate Eq. (7) over the distribution of dose in L:

$$\bar{y}_D = \int \bar{y}_D(L)d(L)dL = \frac{9}{8}\bar{L}_D + \frac{3\delta}{2d}. \qquad (9)$$

With Eq. (6) one therefore obtains the quality factor

$$Q = 0.3\bar{y}_D = 0.34\bar{L}_D + 0.22 \qquad (y\ \text{and}\ L\ \text{in keV}/\mu\text{m}). \qquad (10)$$

For larger values of L Eq. (6) does not apply; one must therefore use Eqs. (2) and (4) instead of Eq. (8). However, the distribution of y for a specified L is then at least for nonrelativistic heavy particles narrow. For relativistic heavy particles it would be more appropriate to use restricted LET, but the influence of this correction is probably minor in comparison to the considerable uncertainty regarding the proper Q values for such radiations. Usually it is therefore a fair approximation to base the quality factor on the value $\bar{y}_D(L)$, rather than the distribution of y.

This establishes the convenient approximation that the quality factor for a specified L is obtained by entering into the function $Q(y)$ the argument $y = 9L/8 + 0.75$,

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

with

$$y = 9L/8 + 0.75 \qquad (L\ \text{and}\ y\ \text{in keV}/\mu\text{m}). \qquad (11)$$

The relation $Q(L)$ is represented and compared to $Q(y)$ in Fig. 5. Similar to the current definition, the quality factor tends toward a constant value at low values of LET. However, in contrast to the present convention, it reaches values substantially less than unity.

The quality factor for an actual radiation field results, as in Eqs. (1) and (2), from an integration:

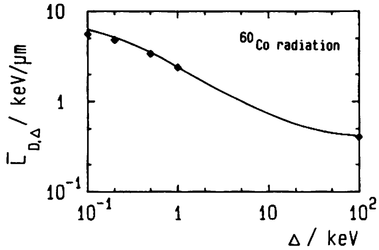

FIG. 6. Dose-average LET for ^{60}Co γ radiation as a function of the cutoff energy. The computations account for all electrons released by unscattered photons. The diamonds are data derived by Blohm (see footnote 1) for the same condition (value for $\bar{L}_{D,\infty}$ inserted at Δ = 100 keV).

$$Q = \int Q(L)d(L)dL. \quad (12)$$

As has been stated, $d(L)$ is the distribution of unrestricted LET. This presents no problems for nonrelativistic heavy charged particles; as seen from Fig. 4 the differences between unrestricted and restricted LET with a cutoff at several keV are minor for such particles and can usually be disregarded.

For electrons the situation is more complicated. At relativistic energies the differences between restricted and unrestricted LET can be substantial, but this has comparatively little influence on Eq. (11). A more important problem is that only part of the electron fluences at energies below the assumed cutoff, Δ, are to be included in the computation of the distribution $d(L)$; the contribution of δ rays with initial energies below Δ is accounted for in the restricted LET and must, therefore, not be counted twice. However, the track ends of the primary charged particles and their higher energy δ rays need to be included. This complexity causes a considerable dependence of the dose average $\bar{L}_D$ on the cutoff energy (see Fig. 6).

For X rays, γ rays, and electrons one must therefore employ a cutoff, and a suitable value is Δ = 5 keV. Equation (10) takes then the slightly modified form

$$Q = 0.3\bar{y}_D = 0.34\bar{L}_{D,5\,\mathrm{keV}} + 0.22 \qquad (y \text{ and } L \text{ in keV}/\mu\mathrm{m}). \quad (13)$$

Values for ^{60}Co γ radiation ($\bar{y}_D$ = 1.9 keV/μm in a 1-μm sphere (*9*) and $\bar{L}_{D,5\,\mathrm{keV}}$ = 1 keV/μm (see Fig. 6)) are in good agreement with this relation. Analogous modifications apply when Q is derived according to Eq. (12).

CONCLUSION

A modified analytical expression has been given which agrees closely with the proposal of the ICRP–ICRU liaison groups for the revision of the quality factor. In contrast to the equation chosen in the report, it establishes proportionality between Q and y at small and moderate values of lineal energy. It has further been shown that roughly equivalent definitions can be given which express the revised quality factor as a function either of the lineal energy or of LET.

While the magnitude of the differences for typical radiation fields has not been assessed in the present article, it appears that there is close equivalence whenever the primary charged particles have ranges substantially larger than 1 μm. For particles of smaller range, e.g., some of the recoils of neutrons below 500 keV and the electrons liberated by photons below 200 keV, the equivalence begins to fail. The definition in terms of L leads then to somewhat larger values of Q than the definition in terms of y; this has been substantiated by computations for typical radiation fields (*17*).

There are other instances where the above relations may fail. An example is the short range electrons produced by soft X rays, but soft X rays are not a major concern in radiation protection. A more interesting special case, of importance in nuclear medicine, is that of Auger emitters such as ^{125}I. The disintegrations of such nuclides release highly localized bursts of electrons. The spatial correlation of the multiplicity of electrons causes considerable energy concentrations in small sites (*18, 19*) and is responsible for the high radiotoxicity of the nuclide. The LET concept cannot account for these matters. The lineal energy measures actual energy concentrations and is thus, in principle, a more meaningful quantity; however, the choice of a 1 μm site is also unsatisfactory in the case of an emitter of short-ranged Auger electrons. While such special cases require further consideration, they do not invalidate the relations which apply to the far more common radiation fields with charged particles of higher energies.

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NOTICE

The Subject Index for Volume 114 will appear in the December 1988 issue as part of a cumulative index for the year 1988.