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ON THE USE OF LET FOR A REVISED QUALITY FACTOR FOR PHOTONS

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Abstract — Linear energy transfer, L, is currently used as reference parameter for the quality factor in radiation protection, and this practice is likely to be continued in an impending revision of the quality factor. But the numerical convention is not, at present, actually applied to photon or electron fields; their quality factor is, instead, summarily equated to unity. The current trend of tightened dose limits in radiation protection may create the need for precise computations of quality factors even for photon and electron radiations. Such computations can, however, not be performed in terms of unrestricted linear energy transfer. The reasons for this difficulty are explained, and the formulae for the quality factor as an integral over electron fluence and restricted linear energy transfer are given. A correct energy balance in this and in a variety of linked dosimetric relations requires a modification of the definition of restricted linear energy transfer. For large energy cut-off values the correction is of minor importance, but for small cut-off values — such as those invoked in biophysical considerations — the modification is essential.

INTRODUCTION

A liaison group of the two International Radiological Commissions, ICRP and ICRU, has proposed a revised quality factor[1]. Even in its tentative form, not yet addressed to Radiation Protection Administrations, the study has provoked controversies with regard to three major issues. First, substantially enhanced quality factors for neutrons have been proposed. Second, it is stipulated that quality factors for photons be different, depending on photon energy. Third, it is suggested that quality factors be linked not to LET but to lineal energy.

There have been arguments for and against LET or y as parameters of the quality factor. LET is especially suited for calculations, y is applicable in measurements. It follows that the choice of either of the parameters has merits and disadvantages, but it is also seen that largely equivalent definitions of the quality factor can be given in terms of LET and y[2,3]. In the interest of conservatism in radiation protection one would, therefore, tend to retain LET as the reference parameter. However, this requires special microdosimetric considerations in the utilisation of the LET concept when it is applied to photon or electron radiations; some of these will be indicated.

LIMITED APPLICABILITY OF UNRESTRICTED LET

Linear energy transfer (LET) is a convenient parameter to characterise radiation quality, when energy transport by δ rays can be disregarded. This approximation can be acceptable for heavy charged particles of low or intermediate energies, but the situation is different for photon and electron radiations, where the contribution to the electron fluence by δ rays can often not be neglected. In calculations, the fluence of primary and secondary electrons can be separated and the absorbed dose is then, under conditions of δ ray equilibrium, equal to

$$D = \int \varphi_p(E)\, L(E)\, dE \qquad (1)$$

L(E) is the (unrestricted) LET of an electron of

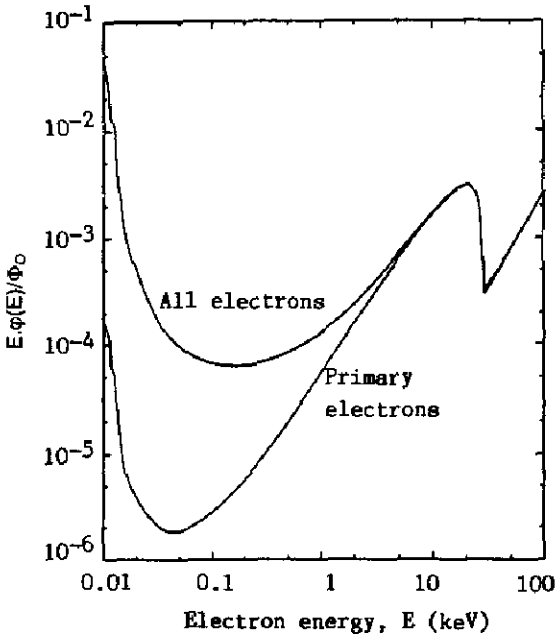

Figure 1. The fluence distribution of electrons for 100 keV unscattered photons in water. The lower curve gives the spectrum of primary electrons, the upper curve that of all electrons. The spectra are normalised to the fluence, Φ_0, of photons.

energy E, and $\varphi_p(E)$ is the fluence distribution in energy of the primary electrons. However, the actual microdistribution of energy imparted is largely determined by the total electron fluence, $\varphi(E)$, which includes a large contribution of δ rays. In measurements, this contribution cannot, usually, be separated out, and Equation 1 is then not applicable. Figure 1 compares the fluences $\varphi_p(E)$ and $\varphi(E)$ that are produced by 100 keV unscattered photons in water; these and subsequent computations for the present study utilise electron collision cross sections by Olivero *et al*[4] which have been developed from fits to measured data predominantly in the energy range up to 10 keV and are, for our purpose, extended up to 100 keV. The actual contribution of the low energy δ rays to the energy imparted is larger than suggested by Figure 1, because the fluence needs to be weighted by the stopping power, which is largest, for electrons in water, at about 100 eV.

L(E) can not be a meaningful parameter when the primary fluence is replaced in the integral by the total fluence. The reason is, that $\int \varphi(E)\, L(E)\, dE$ is, as indicated in Figure 2, substantially larger than the absorbed dose, because some of the energy expended by the electrons is repeatedly added, as it is dissipated by primary electrons and by successive generations of δ rays. This difficulty, well known in dosimetry of photon and electron fields, will have considerable pragmatic importance, if one discontinues the convention that photon and electron radiations are summarily assigned the quality factor 1 in radiation protection. One must then compute the quality factor as an integral over fluence. But any relation:

$$Q = \int Q(L(E))\, \varphi(E)\, L(E)\, dE / D$$
$$= \int Q(L)\, \varphi(L)\, L\, dL / D \qquad (2)$$

will then provide values that are substantially too

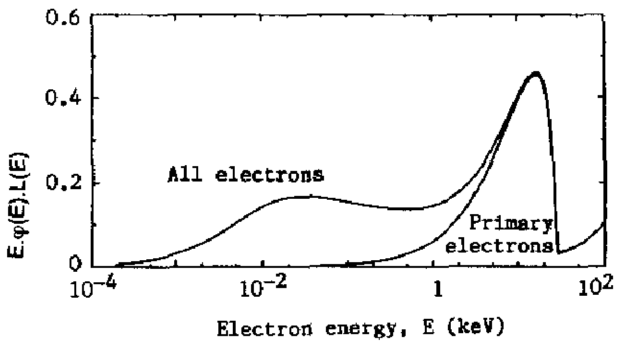

Figure 2. The quantities E $\varphi(E)$ L(E) (upper curve) and E $\varphi_p(E)$ L(E) (lower curve). In this full logarithmic plot, the area under the lower curve equals the absorbed dose (here normalised to unity). The area under the upper curve is considerably larger; this indicates the faulty energy balance that results when unrestricted LET is integrated over the total electron fluence.

large if $\varphi(E)$ or $\varphi(L)$ are the electron fluence spectra in energy or LET.

The error could be avoided if one used the primary electron fluence in the equations rather than the actual fluence. However, this would be meaningless from a biophysical point of view, and it would also be impracticable in unknown radiation fields where one cannot, usually, distinguish the primary fluence from the δ ray fluence. One concludes, therefore, that unrestricted LET is unsuitable for a definition of the quality factor for photon and electron radiations. Instead, one needs to employ a restricted LET, and its definition will, therefore, be considered next.

A MODIFIED DEFINITION OF RESTRICTED LET

Restricted LET, or restricted linear collision stopping power, L_Δ[5], is defined as

$$L_\Delta = dE / dl \qquad (3)$$

where dE is the energy lost along distance dl by a charged particle in collisions with energy loss below Δ.

This definition excludes not only the kinetic energy of emerging 'fast' δ rays, but also the energy expended against their binding energy. For large values of Δ this is irrelevant, but it becomes essential as Δ decreases, and L_Δ vanishes, as Δ approaches zero. Roughly, one can state that L_Δ becomes meaningless at values below Δ=100 eV. This may be one of the reasons for the conventional choice of Δ=100 eV which is an acceptable minimum of Δ, where the present definition of L_Δ is still tolerable.

Rigorous considerations require a more suitable concept, and for the purpose of the present discussion such a concept will be termed reduced LET, Λ_Δ. It is defined as:

$$\Lambda_\Delta = L - dE_\Delta / dl \qquad (4)$$

where dE_Δ is the sum of the kinetic energies of δ rays released along dl with kinetic energies in excess of Δ.

As shown in Figure 3, Λ_Δ agrees with L_Δ for high cut-off values; but it differs substantially for small values of Δ. The limit Δ=0 is admissible for reduced LET, it specifies the linear rate of energy expended against binding energies per unit path length. $\Lambda_0(E)$ is a precisely defined concept and can be readily calculated, if the differential cross sections for the energy loss of the primary charged particle are known, for every subshell of the target molecules. $\Lambda_0(E)$ is essentially equivalent to the notion of 'primary ionisation density' but is more accessible to numerical evaluation.

The absorbed dose, D, can be expressed in terms of $\Lambda_0(E)$

$$D = \int \varphi(E)\, \Lambda_0(E)\, dE \qquad (5)$$

where $\varphi(E)$ is the fluence distribution in energy of all electrons, (see upper curve in Figure 1). Corresponding relations have earlier been given by Spencer and Attix[6] and by Alm-Carlsson[7].

The differential distribution of absorbed dose in electron energy is exemplified in Figure 4, and is compared with the contribution of the primary electrons alone.

A SIMPLE SCALING RELATION

As suggested by Figure 5, one can express Λ_Δ/Λ_0 in terms of the scaling parameter, τ_Δ

$$\Lambda_\Delta(E) = \Lambda_0(E)\, \tau_\Delta \qquad (6)$$

τ_Δ is nearly independent of E for energies in excess of 2Δ. However this may be partly an artefact of the empirical formulae that Olivero *et al*[4] have chosen to represent the cross sections differential in energy, W, of the emerging δ rays. In these formulae the cross sections for each shell are represented by the product of an expression that depends only on the energy of the colliding electron and an expression that depends on W, with the added constraint $W \leqslant E/2$. For each shell one obtains, therefore, the scaling relation of Equation 6 with constant τ_Δ, the slightly changing contributions of the individual shells with varying energy of the impinging electron leads only to a very weak dependence of τ_Δ on E, as shown in Figure 5.

The scaling relation of Equation 6 is in line with arguments repeatedly emphasised by Harder[8–10], that relate to energy deposition by electrons in small volumes and that had been verified by Monte Carlo simulations. It simplifies the calculation of $\Lambda_\Delta(E)$, since it makes it sufficient to know $\Lambda_0(E)$ and the factor τ_Δ.

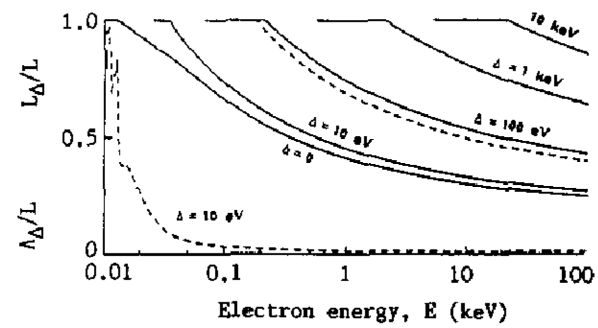

Figure 3. Ratio, $\Lambda_\Delta(E)/L(E)$, of the reduced LET to unrestricted LET of electrons in water (solid lines) and the corresponding ratio, $L_\Delta(E)/L(E)$, of restricted LET to unrestricted LET (broken lines).

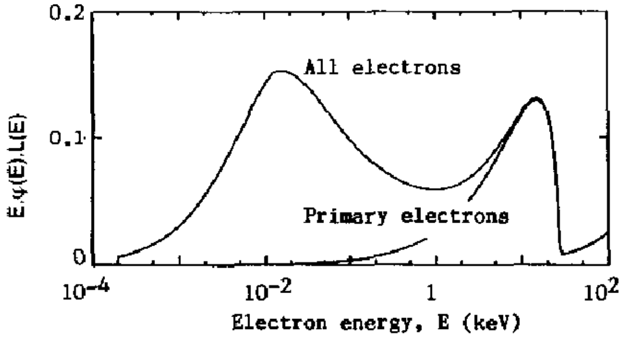

Figure 4. The distributions of absorbed dose contributed by electrons of specified energy, released in water by 100 keV unscattered photons; lower curve, primary electrons only; upper curve, all electrons, including δ rays.

CORRECT FORM OF THE EQUATION FOR THE QUALITY FACTOR

In principle one could define the quality factor in terms of $\Lambda_0(E)$

$$Q = \int_0^\infty Q(\Lambda_0(E))\, \Lambda_0(E)\, \varphi(E)\, dE \,/\, D \qquad (7)$$

This would permit the use of the actual fluence distribution, $\varphi(E)$, without faulty energy balance. However, the approach is impracticable, because the integral is, as is evident from Figure 4, largely determined by the fluence of low energy electrons; in the example of Figure 4 one finds that 60% of the absorbed dose is delivered by electrons below 100 eV. In this energy range $\varphi(E)$ is difficult to determine, and, furthermore, the stopping power is inadequately known. In practice one must, therefore, utilise restricted LET with a substantial energy cut-off. The integral over the fluence must then extend merely down to Δ. The reason is that the major part of the fluence below Δ is already accounted for in $L_\Delta(E)$, or in the modified quantity

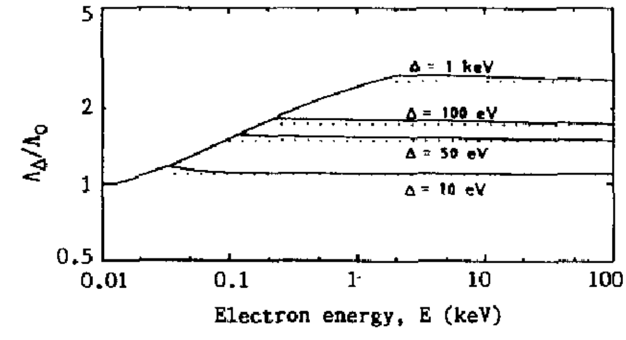

Figure 5. The ratio, $\Lambda_\Delta(E)/\Lambda_0(E)$, for electrons in water for specified cut-off energies. Lines of constant value are indicated by dots.

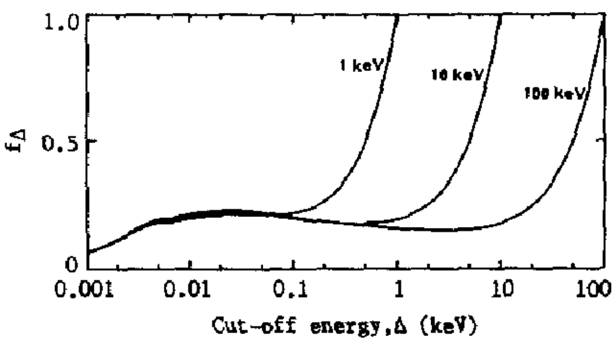

Figure 6. The fractional contribution, f_Δ, of 'track ends' to the absorbed dose for electrons of specified initial energy in water.

$\Lambda_\Delta(E)$. However, one needs to account in addition for the track ends, with kinetic energies below Δ, of the primary electrons and of the 'fast' δ rays, i.e. those δ rays that are released with energies in excess of Δ. Assigning to the track ends an appropriately calculated quality factor, Q_Δ, one obtains the relation

$$Q = \int_\Delta^\infty Q(L_\Delta(E))\, L_\Delta(E)\, \varphi(E)\, dE / D + Q_\Delta f_\Delta \qquad (8)$$

where f_Δ is the fraction of absorbed dose delivered by the 'track ends'; this fraction is typically of the order of 15% (see Figure 6). In Equation 8 we make use of the convention, that $L_\Delta(E)=L_\infty(E)$ for $E<2\Delta$.

The symbol L_Δ is used here, because it is expected that the modified definition of restricted LET will replace the current definition; the term 'reduced LET' and its symbol will then be unnecessary. One notes, furthermore, that L_Δ and Λ_Δ are substantially equal at large cut-off values, Δ.

The equations for Q_Δ and f_Δ are straightforward, but their explicit form is immaterial for the present general considerations. The essential point is, that unrestricted LET must not be naively applied in a revision of the quality factor that assigns different values of Q to different photon energies.

CONCLUSION

Definitions of the quality factor in terms of lineal energy, y, and in terms of linear energy transfer, L, can be largely equivalent. It is, therefore, suggested that the familiar reference parameter L be retained without excluding the possibility of using y in measurements.

Utilisation of the reference parameter, unrestricted linear energy transfer, L, is practicable for heavy ions or the recoils of neutron radiation. For photon and electron radiations, however, it leads to inconsistencies. One must, therefore, employ restricted LET, and the nature of the resulting equation for Q — irrespective of the specific definition of Q as a function of LET — has here been considered.

Restricted LET, according to its present definition, is adequate for the definition of the quality factor. The reason is that one can choose a large value of the cut-off energy, for example $\Delta=5$ keV. Any application of LET that involves small values of Δ, of the order of 100 eV or less, requires, however, a modified definition of restricted LET which needs to replace the present convention.

ACKNOWLEDGEMENT

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