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Criteria for the Applicability of LET[1]

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KELLERER, A. M., AND CHMELEVSKY, D. Criteria for the Applicability of LET. *Radiat. Res.* 63, 226–234 (1975).

Linear energy transfer is only one of the factors which determine energy deposition in microscopic regions. Other factors are the range of charged particles, energy loss straggling, and energy dissipation by delta-rays. Graphs are presented delineating those regions of site diameters and particle energies for which the individual factors are important. In the case of protons and other heavy ions one finds a substantial interval of site diameters and particle energies for which the LET concept is appropriate, i.e., where LET is the only relevant factor. No such interval exists for electrons.

INTRODUCTION

Linear energy transfer (LET) and related concepts have been introduced in order to evaluate the energy deposited by charged particles in microscopic regions (*1–4*). Since LET is only a statistical mean, a rigorous analysis must be based on the microdosimetric quantities which account for the statistical processes in energy deposition (*5–7*). There are, however, cases in which LET is a useful approximation, not only in qualitative comparisons of different radiation types, but also in numerical evaluations. Various authors have dealt extensively with this point (*1–4, 8–12*). Nevertheless, it is often difficult to judge the applicability of LET in a specific situation. Criteria for its range of validity are therefore desirable.

FACTORS RELEVANT TO ENERGY DEPOSITION

The situation which will be considered in the following is the traversal or partial traversal of a microscopic spherical site of diameter d by a charged particle. The amount of energy deposited in the site in such an event is a statistical variable, and various factors determine the probability distribution of this variable.

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The most elementary factor is the random distribution of chord lengths in the site. Even if the particle track is treated as an infinite straight line with uniform rate of energy loss, L, one deals with variations of the energy deposition from the maximum value, Ld, for central traversals to arbitrarily small values for glancing traversals. It has been shown (*13*) that the resulting distribution of energy imparted, ϵ, is triangular:

$$p(\epsilon) = 2\epsilon/(Ld)^2 \qquad 0 < \epsilon \leq Ld, \tag{1}$$

that the mean chord length is $\bar{l} = 2d/3$, and that the relative variance V_C is (*14*):

$$V_C = \sigma^2/\bar{\epsilon}^2 = \tfrac{1}{8}. \tag{2}$$

This random factor need not be considered a limitation of the LET concept since it can readily be accounted for in those cases where it is relevant (*13*, *15*). Moreover, the factor is usually unimportant compared to the fluctuations due to the variations in LET. The relative variance of the LET distributions is $V_L = \bar{L}_D/\bar{L}_T - 1$ where $\bar{L}_D$ and $\bar{L}_T$ are the dose and the frequency mean of the LET-distribution (*12*). It has been found (*14*) that the relative variance of the energy imparted to the site in individual particle passages is:

$$V = V_C + V_L = \tfrac{1}{8} + (\bar{L}_D/\bar{L}_T - 1), \tag{3}$$

where the second terms is dominant except in the so-called track segment experiments (*16*, *17*).

Energy loss straggling, the radial extension of the particle tracks, and the finite range of the particles are additional factors which can influence the spectrum of energy deposition. Their influence will be considered next.

If the particle range is large as compared to the site diameter, the change of LET while the particle traverses the site can be neglected. Under this condition the relative variance of energy deposition due to energy loss straggling is (*14*):

$$V_S = \delta_2/\bar{\epsilon} \tag{4}$$

where $\bar{\epsilon}$ is the mean total energy transferred to the site in a traversal, and δ_2 is the energy mean of the energy transferred in individual collisions. Let $w(\epsilon)d\epsilon$ be the fraction of collisions which are associated with energy transfer between ϵ and $\epsilon + d\epsilon$. Then δ_2 is defined as (*14*):

$$\delta_2 = \int_{\epsilon_{\min}}^{\epsilon_{\max}} \epsilon^2 w(\epsilon)d\epsilon \Big/ \int_{\epsilon_{\min}}^{\epsilon_{\max}} \epsilon\, w(\epsilon)d\epsilon \tag{5}$$

A numerical approximation of this quantity will be used in the next section.

It has been demonstrated that with the factors considered up to this point the relative variance of the energy transfer in individual particle passages is (*14*):

$$V = V_C + V_L + V_S = \tfrac{1}{8} + (L_D/\bar{L}_T - 1) + \delta_2/\bar{\epsilon}. \tag{6}$$

This additivity of the increments of the relative variance due to the different factors permits a comparison of the role of energy loss straggling with that of chord-length variations and of variations of LET. The relative variance, as a dimensionless quantity, has the advantage that its value is the same for the distribution of energy imparted in individual events and for the commonly used event spectra $f(y)$ or $f_1(z)$ which refer to lineal energy or specific energy (*18, 19*) instead of energy imparted.

The situation is complicated by the additional factor that for sufficiently small sites and for sufficiently fast charged particles delta rays can escape from the region of interest or enter it. The energy lost by the charged particle in an event can not then be equated with the energy imparted to the site. This factor must be considered whenever the distance-restricted (*12*) linear energy transfer, L_r, with r equal to the radius of the site, is significantly smaller than the total unrestricted linear energy transfer, L_∞. The numerical criterion which will be chosen in the next section is $L_r \leq 0.9\, L_\infty$, i.e., 10% or more energy dissipation beyond the distance r from the track core. In Eq. 6 the factor expresses itself in a reduction of the value δ_2 which must be considered the mean energy imparted to the site as the result of a collision and not the mean energy lost by the particle due to a collision.

The last possibility which must be considered is that of incomplete traversals and of a significant change of LET of the particle while it traverses the site. In the case of electrons one must also consider the possibility of a substantial curvature of the track segment. The influence of these factors can not be quantified in a simple relation as Eq. (6). However a general criterion is that these factors are insignificant if the range of the particle is large compared to the dimension of the site.

NUMERICAL EVALUATION OF THE INDIVIDUAL FACTORS

The object of this section is to determine those charged particle energies and site diameters for which the factors finite track length, energy loss straggling, and delta-ray escape can be neglected.

Assume that the range of the proton is R and that $\bar{l} = 2d/3$ is the mean chord length in the site. Then the mean segment length, $\bar{s}$, of the track in the site is (*20*):

$$\bar{s} = \left(\frac{1}{\bar{l}} + \frac{1}{R}\right)^{-1} \tag{7}$$

For $R = 10\,\bar{l}$ one obtains $\bar{s} = 0.91\,\bar{l}$, i.e., a reduction of less than 10% in segment lengths because of incomplete passages. Furthermore, one finds that for charged particles the LET changes by less than 5% if the range changes by 10%. A reasonable criterion for disregarding the finite range of the particle and the gradient of LET is therefore $R > 6d$. In Fig. 1 the region I corresponds to those combinations of site diameter, d, and proton energy, E, for which the criterion is not met. This is therefore the region where the finite proton range must be taken into account. The ranges and stopping powers used in the present analysis are those given by ICRU (*12*) for water.

The second factor which will be assessed is energy-loss straggling. Here we will choose the criterion that the contribution of straggling to the relative

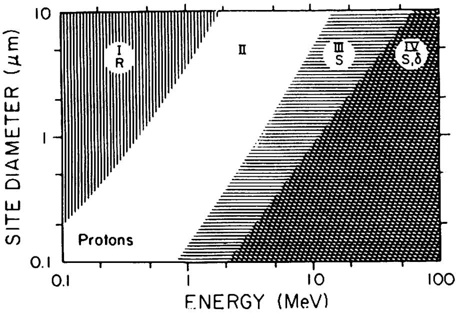

FIG. 1. Diagram of the ranges of site diameters and proton energies where other factors in addition to LET are relevant to energy deposition. The symbols R, S, and δ identify those domains in which limited particle range, energy-loss straggling, and energy dissipation by delta-rays are pertinent. In region II LET is the only relevant factor.

variance at the initial energy, E, of the particle is less than the value $\frac{1}{8}$ which corresponds to the chord-length variations in the sphere. Thus:

$$V_S = \delta_2/\bar{\epsilon} = 3\delta_2/2Ld \leqslant \tfrac{1}{8}, \tag{8}$$

where L is the LET at the initial energy of the particle. Accordingly one has:

$$d \geq 12\delta_2/L. \tag{9}$$

δ_2 can be approximated by the value which results (*14*) from the so-called free electron model:

$$\delta_2 = \epsilon_{\max}/2\, ln(\epsilon_{\max}/I), \tag{10}$$

where I is the mean excitation energy of the medium and $\epsilon_{\max}$ is the maximum delta-ray energy. In the case of sufficiently energetic but nonrelativistic protons of energy E one has $\epsilon_{\max} = E/459$. With this value and with $I = 65$ eV one obtains the values δ_2 given in Fig. 2. One may note that these values are some-

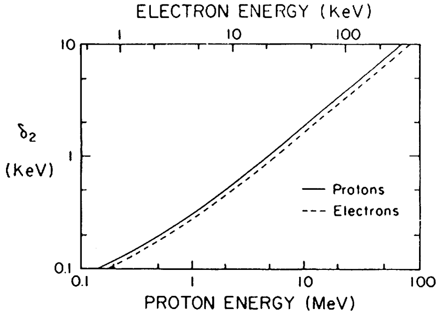

FIG. 2. Energy mean, δ_2, of the energy loss of protons and electrons in individual collisions. The values correspond to the so-called free electron model and are calculated for $I = 65$ eV according to Eqs. (10) and (11). For protons the $1/\epsilon^2$-spectrum is used, for electrons, the Mott cross section. The energy scales are superimposed in such a way that the maximum delta-ray energy for the protons corresponds to half the electron energy.

what too small because they do not account for the binding energies of the electrons [see for example (*21–24*)]. This inaccuracy is, however, not significant in the present context. Inserting the data of Fig. 2 in Eq. (9) one finds that straggling can be disregarded in regions I and II while it must be taken into account in region III and IV.

Finally we consider the radial extension of the particle track, i.e., the energy dissipation by delta-rays which may leave or enter the site. The criterion for disregarding this factor will be that at the initial kinetic energy, E, of the particles less than 10% of the transferred energy is dissipated further than a distance r from the track core. The fractional escape of energy from a sphere of radius r is larger than that out of a cylinder of radius r around the track core; this aspect has been treated numerically in an earlier publication (*25*). The radial profiles of energy deposition as a function of distance from the track core are not accurately known, and experimental data exist only for protons up to 3 MeV (*26*). But using theoretical extrapolations (*26*) of these data one finds that the radial extension of the track and the energy dissipation by delta-rays must be accounted for in region IV.

In Fig. 1 the various regions are marked by symbols indicating the factors which must be considered in addition to LET. R stands for the finite range of the particle and the gradient of LET on its track; S stands for energy loss straggling; and δ stands for energy dissipation by delta-rays. One concludes that in a substantial range of site diameters and particle energies, namely in region II, the LET concept is appropriate, i.e., applicable without consideration of additional factors. If one goes to larger site diameters or to smaller particle energies one has to account for the finite range of the particles. If one goes to smaller sites or larger particle energies one must first account for straggling and ultimately also for the energy dissipation by delta-rays.

In dealing with neutron irradiations one must determine those regions into which significant fractions of the recoil protons fall, and must then consider the factors which apply to these regions. For example one finds for a site diameter of 1 μm, that energy loss straggling and, *a fortiori*, delta-ray structure can be neglected at least up to about 4 MeV. For larger site diameters straggling can be disregarded at even higher neutron energies. Computations of energy depositions spectra for neutrons such as the ones performed by Caswell and Coyne (*27*, *28*) can therefore be quite valid even if straggling is neglected. If the neutron energies or site diameters fall into region III the results may still be useful approximations, but at least those data which correspond to the more energetic recoils are then inaccurate. A precise analysis would therefore have to account for energy loss straggling. Only for still larger energies or smaller site diameters will it be necessary to consider the range of the delta-rays.

Analogous schemata can be derived for heavier charged particles. For this purpose it is practical to plot the kinetic energy per nucleon on the abscissa. The stopping power increases as the square of the effective charge, Z', and the range changes by the factor A/Z'^2, where A is the atomic weight of the particle. The spectrum of delta-rays and therefore the quantity δ_2 and the radial distribution of energy around the track core remain unchanged.

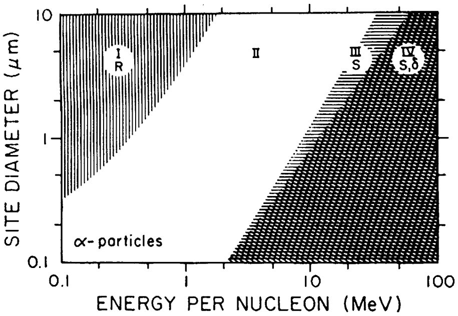

FIG. 3. Diagram of the ranges of site diameters and energies of alpha-particles where other factors in addition to LET are relevant to energy deposition. The symbols R, S, and δ identify those domains in which limited particle range, energy-loss straggling, and energy dissipation by delta-rays are pertinent. In region II LET is the only relevant factor.

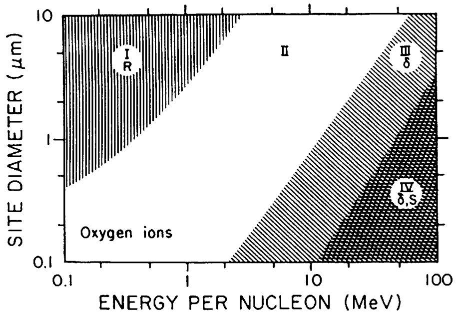

FIG. 4. Diagram of the ranges of site diameters and energies of oxygen ions where other factors in addition to LET are relevant to energy deposition. The symbols, R, S, and δ identify those domains in which limited particle range, energy-loss straggling, and energy dissipation by delta-rays are pertinent. In region II LET is the only relevant factor.

Accordingly the region where the limited particle range must be considered is shifted by the factor A/Z'^2 in site diameters. The region where straggling must be accounted for is reduced by the factor Z'^2 towards smaller site diameters. The region where energy dissipation by delta-rays plays a role remains unchanged.

Using stopping powers and ranges for water[3] one obtains Fig. 3 for alpha-particles. In this case the region of validity of LET is larger than for protons. Energy loss straggling and energy dissipation by delta-rays are about equally critical factors for α-particles.

For even heavier ions the energy dissipation by delta-rays is the dominant factor and energy loss straggling is comparatively insignificant. Figure 4 repre-

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[3] P. G. STEWARD, Stopping-power and range-energy data of heavy ions in nongaseous media. In *Biomedical Studies with Heavy Ion Beams*, pp. 8–12. University of California, Lawrence Radiation Laboratory Report, UCRL-17357, 1967.

sents as an example the case of oxygen. The range of applicability of LET is similar to that for alpha-particles. This remains true even for much heavier ions.

Finally we consider the other limit, namely that of electrons. One may again use the criterion $R \geq 6d$ as a condition for disregarding the finite particle range; this is also a sufficient condition for disregarding the curvature of the track segment in the site. This criterion separates regions I and II from III and IV in Fig. 5. As far as energy loss straggling is concerned one could use the values δ_2 for protons by simply choosing those proton energies which correspond to a maximum delta-ray energy equal to half the electron energy. However a more accurate estimate is obtained by an evaluation of the Mott formula [see for example (*29, 30*)]. Inserting the Mott cross section into Eq. (5), and setting the lower limit of the first integral in this equation equal to zero and the lower limit of the second integral equal to $\epsilon_{\min} = 2I^2/E$, one obtains:

$$\delta_2 = \frac{[\frac{5}{2} - 3\ln(2)]E}{2\ln(E/4I) + 1} = \frac{0.21E}{\ln(E/I) - 0.885} \tag{11}$$

where E is the kinetic energy of the electron and I the excitation potential. The resulting values are represented by the broken line in Fig. 2, where electron and proton energies are superimposed in such a way that they are associated with the same maximum delta-ray energy. With these values and with Eq. (9) one obtains region I in Fig. 5 as the domain of electron energies and site diameters for which straggling can be neglected.

Energy dissipation by delta-rays is more difficult to evaluate for electrons because the radial profiles of energy deposition are not accurately known. In the absence of precise information it is a reasonable assumption that the radial profile is equal to that which is obtained with heavier particles for the same maximum delta-ray energy. With this approximation one finds that energy dissipation by delta-rays must be considered in region IV in Fig. 5.

The important conclusion from Fig. 5 is that for electrons there is no region of energies and site diameters where LET is appropriate. Energy loss straggling,

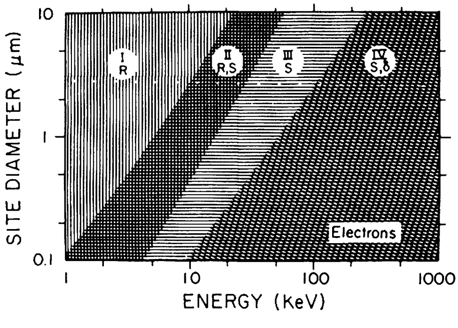

FIG. 5. Diagram of the ranges of site diameters and electron energies where various factors in addition to LET are relevant to energy deposition. The symbols R, S, and δ identify those domains in which limited particle range, energy-loss straggling, and energy dissipation by delta-rays are pertinent. There is no region where LET is the only relevant factor.

or the finite particle ranges and the curvature of the tracks must always be taken into account in quantitative evaluations of energy deposition.

CONCLUSIONS

There are three main factors which in addition to LET determine energy deposition in cellular or subcellular regions. These factors are the finite range of charged particles, the energy loss straggling of charged particles, and the dissipation of energy by delta-rays. For protons there is a considerable range of site diameters and particle energies where the role of these three factors is insignificant and where the LET concept is therefore appropriate. Outside this region towards smaller particle energies and larger site diameters one must take into account the reduction of energy deposition due to incomplete passages of the particles through the site. Beyond the region towards smaller site diameters and larger particle energies one must account for energy loss straggling. While energy dissipation by delta-rays is less important than energy loss straggling, it can also become significant at very small site diameters and large particle energies.

Similar results are obtained for heavier ions. However energy loss straggling becomes less important for these particles and the limiting factors for high particle energies and small site diameters is energy dissipation by delta-rays.

For electrons one can never simultaneously meet the two conditions that the site diameter is small enough to keep incomplete traversals at an insignificant level, and large enough to limit energy loss straggling. At least one of these two factors must therefore always be considered in addition to LET.

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