MODIFIED TARGET THEORY - DOSIMETRIC IMPLICATIONS

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Introduction.

Conventional dosimetry systems based on energy parameters such as absorbed dose and LET become invalid for heavy charged particles (e.g. H, C, N and O ions) at energies near and below the Bragg peak because (i) the LET is not single valued and consequently there is ambiguity in the dose-response relationship, and (ii) there are competing types of energy absorption process which may act with different degrees of effectiveness. This has important practical consequences in the dosimetry of intermediate energy neutrons and of heavy particles near the end of their range.

In the following discussion target theory (1) is re-explored and modified in the light of modern knowledge. The choice of parameters for conventional dosimetry systems is considered and an alternative approach which could lead to a new universal system of dosimetry is suggested. For illustrative purposes comment is confined to the simple special case of single target, single hit theory but it should be borne in mind that the ideas are easily extended to more complex situations.

Basic Target Theory.

Good correspondence with the general shape of dose-response curves is obtained by assuming the stochastic nature of radiation interactions and that Poisson statistics apply. Thus the survival probability P, for single hit inactivation is given by

$$P_1 = e^{-vC} \quad \text{----------(1)}$$

where 'v' is the geometric volume of the sensitive site and C is the concentration of hits per unit volume. When the absorbed energy, D, is chosen as a parameter then the energy action coefficient μ must be introduced to convert dose to concentration. This necessitates the 'hit' be re-defined as the mean amount of energy required to produce the response. The energy action coefficient is thus a measure of the efficiency of the utilisation of energy or the reciprocal of the mean energy per inactivation. Equation (1) is rewritten as

$$P_1 = e^{-v.\mu.D} \quad \text{---------(2)}$$

μ is rarely written explicitly because it is usually taken (erroneously) as a constant of proportionality.

If the natural logarithm of the survival probability is plotted against absorbed dose, D, a straight line of gradient $-v\mu$ is obtained. Typical results for various radiations in ribonuclease (2) show that the gradient (and hence μ) decreases with increasing LET due to (i) energy wastage by saturation but this is counteracted to some extent by (ii) more efficient spatial use of energy by the δ-rays and (iii) possible increased efficiency associated with the chemical action of the physical interaction products.

As an alternative to using v, μ, and D as parameters one may use the effect cross-section σ_H and the radiation fluence Φ. For track segment experiments $\Phi = D/L$ and

$$\therefore \quad \sigma_H = v.\mu.L \quad \text{----------(3)}$$

Originally it was thought that as L increased, σ_H would tend towards σ_g the geometric cross-section but experiment showed that σ_H may be many times the geometric cross-section due, at least in part, to the spatial distribution of the δ-rays associated with high LET radiations. Here, the spatial effect is included within the detailed formulation of μ.

Energy absorption processes for slow ions.

Experimental data (3) for proton and heavier ion inactivation of enzymes indicates that elastic scatter interations are for equal energy deposition much more efficient at producing damage than are simple ionising collisions. Hence, allowance ought to be made for the partition of energy into protons associated with each type of energy absorption process.

A modified target model has been proposed (4) which takes into account the following important factors : direct primary, secondary and subsequent interactions; the (indirect) chemical action of the slowed down products; the spatial distribution of the secondary particles released in the direct interactions; event or energy wastage due to saturation (overkill) in the targets; different damage efficiency for different types of interaction process.

Modified Target Model (single target, single hit).

Let ${}^{i}N_p$ be the mean number (m) of interactions produced in a primary target. ${}^{i}N_p$ is limited to a maximum of unity to allow for saturation by use of the Poisson probability P(m). Let $\bar{n}$ be the number of secondary targets inactivated by a secondary particle assumed to have the mean energy of the secondary particle spectrum. If the target has a geometric cross-section σ_g then the total hit cross-section for a radiation of type i is

$${}^{i}\sigma_H(E) = {}^{i}\sigma_{H,p}(E) + {}^{i}\sigma_{H,s}(E) + CC \quad \text{---------(4)}$$

where the primary contribution ${}^{i}\sigma_{H,p}(E) = \sigma_g \cdot P_1(m)$

the secondary contribution ${}^{i}\sigma_{H,s}(E) = \sigma_g \cdot {}^{i}N_p \cdot \bar{n}$

and the chemical contribution $CC = \sigma_g \left\{ \bar{\varepsilon}_j \, {}^{i}N_p + {}^{i}N_p \sum_{r=1}^{n} (\bar{\varepsilon}_k \, {}^{j}N_k) \right\}$

($\bar{\varepsilon}_j$ and $\bar{\varepsilon}_k$ are respectively the mean chemical action efficiencies for the primary j and seconiary k particles).

Better appreciation of the significance of the formula may be obtained by examining a simplified version appropriate to low LET radiation.

Simplified Cross-Section. ($d \ll \lambda$)

If the mean free path λ between interactions is very much greater than the mean chord length d through the target i.e. valid for fast charged particles of low LET then $\bar{\varepsilon}_j \sim \bar{\varepsilon}_k = \varepsilon$ and $P_1(m) \doteq {}^{i}N_p$. then

$$ {}^{i}\sigma_H(E) = \sigma_g \cdot {}^{i}N_p \, (1 + \bar{n})(1 + \varepsilon) \text{ -------(5)} $$

or in alternative form using the target volume v and macroscopic cross-section ${}^{i}\Sigma_p$

$$ {}^{i}\sigma_H(E) = v \cdot {}^{i}\Sigma_p \cdot (1 + \bar{n})(1 + \varepsilon) \text{ ----------(6)} $$

Dosimetry parameters.

1) The absolute value of the biomolecular (biological) effectiveness in a fluence φ_i of radiation type i is given by the damage parameter

$$ {}^{i}\sigma_H \cdot \varphi_i = (1 + \varepsilon) \cdot v \cdot C \text{ ----------(7)} $$

Thus the original survival probability e^{-vC} becomes $e^{-(1 + \varepsilon) \cdot v \cdot C}$. Note that the RBE is given simply by the ratio of the effect cross-sections.

2) The additive parameter (cf dose equivalent, H) for different radiations i is ${}^{i}\sigma_H \cdot \varphi_i$.

3) The radiation quality is defined by the parameters $(1 + \varepsilon)(1 + \bar{n}).^{i}\Sigma_{p}$ and v. Note that the biological and physical parameters are not separable because of the existence of $\bar{n}$ and possibly ε.

4) The energy action coefficient μ can be expressed in terms of the fundamental interactions by

$$\mu = \frac{(1 + \varepsilon)(1 + \bar{n}).^{i}\Sigma_{p}}{L} \qquad \text{----------(8)}$$

Fig. 1 shows the reciprocal of μ for H, He and N ions incident on ribonuclease where it will be seen that μ is not constant. This energy region is of practical relevance to intermediate energy neutron dosimetry.

5) For single hit action the survival probability should be written as

$$e^{-v.\sum_{r}\mu_{r}.D_{r}} \qquad \text{----------(9)}$$

where D_r is the partition of the total absorbed dose expended in process type r or as $e^{-\sum_{i}{}^{i}\sigma_{H}.\Phi_{i}}$ where i denotes the radiation type

Examination of equation (7) suggests that if values of ε can be deduced for different target groups e.g. enzymes, viruses, cells etc. then measurement of the concentration of events (e.g. free electrons, free H atoms, etc.) combined with a knowledge of the geometric volume of the target may permit construction of a new system of dosimetry without need for the energy parameters required in the more conventional approach (cf equations 8 and 9).

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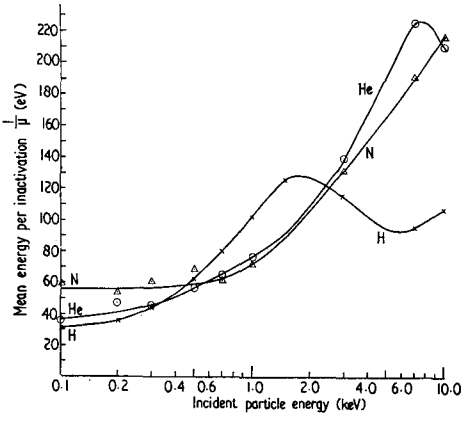

Fig. 1. Mean energy per inactivation of a ribonuclease molecule for H, He and N projectiles. On the left side of the maxima damage is primarily due to elastic scattering and on the right side to ionisation.

References

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