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SESSION 7 (cont.)

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CONCEPTS AND QUANTITIES RELEVANT TO THE EVALUATION OF CHARGED PARTICLE TRACKS

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ABSTRACT: The stochastic variables ε, z and y have originated in close connection with experimental microdosimetric techniques, and their definitions reflect these techniques. Recently other quantities have been defined that correspond more closely to the computational approach in microdosimetry. Of particular importance among the new concepts is the notion of *energy transfers* and that of the *distance distribution* t(x). These notions are considered.

A general equation for dual radiation action (lesions produced by pairs of sublesions) can be formulated in terms of t(x) and an analogous function s(x) that describes the geometry of the sensitive structures in the cell. This formula is a general equation for the random overlap of two geometrical objects (particle track and sensitive structures of the cell); it determines the magnitude of the linear component for the formation of lesions. As a further illustration of the implications of the distance distribution t(x) the concept of *intra-track dose* $\Delta(x)$ is introduced.

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Introduction

Microdosimetry is the part of dosimetry that deals with the statistical fluctuations of energy absorption in irradiated matter. Stochastic quantities such as *energy imparted* ε *specific energy* z and *lineal energy* y describe these fluctuations. Their probability distributions (usually restricted to spherical regions) have been the object of experimental as well as theoretical studies. In fact microdosimetry is sometimes, in a somewhat too narrow definition, identified with the study of the probability distributions of ε, z or y.

The established stochastic quantities ε, z, and y are important and useful; however other quantities and concepts have been introduced which may eventually assume an equally important role. These notions have originated from the evaluation of charged particle tracks and they will here be summarized. The definition of energy imparted can serve as a starting point for their consideration.

The notion of energy transfers and the definition of energy imparted

Energy imparted is the fundamental stochastic quantity of dosimetry. It is defined as the difference of radiation energy (kinetic energy of ionizing particles[+)]) flowing into and flowing out of the reference volume (1).

Details of the definition that account for the change of rest mass in particle transformations need, for the present purpose, not be considered.

The ICRU definition of energy imparted is schematically represented in Fig.1a. This definition refers to finite domains and invokes merely the overall inflow and outflow of radiation energy. It does not account for the actual processes of energy transfer within the volume nor does it account for their spatial distribution. The definition corresponds therefore to the experimental determination of the quantities ε, z, or y, where total energy

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[+)] The term *ionizing* has not been explicitely defined in ICRU report 19. In the present context it is sufficient to note that certain minimum kinetic energies can arbitrarily be specified for various types of particles so that these particles are not considered as ionizing if their kinetic energy (i.e. energy minus rest energy) is below the specified value.

transfer (approximated in terms of total number of ions) is determined without regard to the spatial distribution within the sensitive region of the detector.

Carlsson (2) has recently proposed a definition of energy imparted that is equivalent to the ICRU definition but has a different form. In this definition the energy imparted is the sum of contributions $\Delta\varepsilon_i$ from individual processes, such as electronic collisions, occurring in the reference volume. This form of the definition corresponds to those recent microdosimetric studies which utilize the actual coordinates of charged particle tracks. In fact the definition of the contributions $\Delta\varepsilon_i$ is identical with the definition of *energy transfers*[+)] in the evaluation of charged particle tracks (3).

Energy transfers $\Delta\varepsilon_i$ are defined for those points T_i where ionizing particles undergo an interaction. Each point T_i is termed a *transfer point*. The value $\Delta\varepsilon_i$ is equal to the kinetic energy of the ionizing particle incident on the transfer point minus the kinetic energy of the ionizing particle(s) emerging from the point.

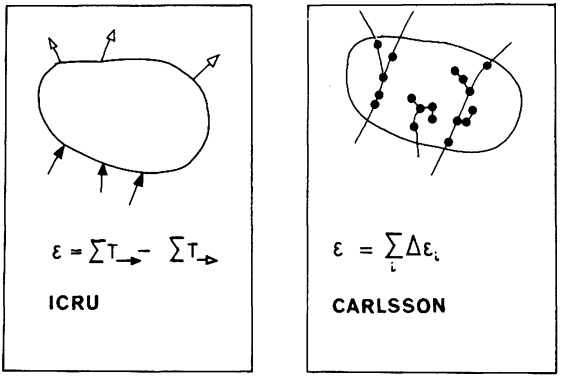
It must be noted, that kinetic energy is not counted if it is lower than the limit specified for ionizing particles. This implies that energy dissipation by non-ionizing particles is disregarded. There will be numerous transfer points where an incident ionizing particle loses sufficient energy to emerge as a non-ionizing particle. The number of emerging ionizing particles may then be zero, and the energy transfer is simply equal to the kinetic energy of the incoming particle.

It will also be noted that interactions between charged particles do not, strictly, take place at a point. For the purpose of the present discussion this can, however, be disregarded.

For those details of the definition that deal with changes in rest mass in particle transformations one may refer to the article by Carlsson.

[+)] The energy transfers have earlier (3) been symbolized by ε_i, but Carlsson's notation $\Delta\varepsilon_i$ is now used.

The definition of energy imparted in terms of individual energy transfers is schematically represented in Fig.1b. In this figure dots stand for the energy transfers $\Delta\varepsilon_i$.



1a 1b

Fig.1 Two equivalent definitions of *energy imparted*.

The symbols $T_{\rightarrow}$ and $T_{\triangleright}$ in Fig.1a stand for the kinetic energies of incident and out-going particles.

The dots in Fig.1b represent energy transfers $\Delta\varepsilon_i$ that may be ionizations or excitations.

The spatial pattern of energy transfers as an explicit description of particle tracks

The coordinates of all energy transfers together with the values $\Delta\varepsilon_i$ afford a nearly exhaustive description of a charged particle track. The term *particle track* is here used to designate energy deposition by a particle and its ionizing secondaries.

The spatial distributions of energy transfers are usually obtained by Monte Carlo methods (4,5). Similar information is sought in experiments that aim at the determination of the coordinates of individual ionizations in a cloud chamber (6). The unprocessed information, i.e. the collection of the coordinates of energy transfers, could in principle be utilized directly in a Monte Carlo superposition of simulated charged particle tracks and simulated cellular structures. However this will often require detailed information on critical cell organelles that is not available. It is therefore desirable to obtain a characterization of the spatial pattern of energy transfers that is more compact and that can be applied in a more general way. The *distance distribution*, t(x), of energy transfers is such a compact characterization.

The distance distribution t(x) *as an implicit description of the charged particle tracks*

The microscopic distributions of energy produced by different types of ionizing radiations vary by the degree of spatial correlation of energy transfers. With entirely uncorrelated energy transfers (random distribution of transfers) there would be no increased probability for other energy transfers in the vicinity of a transfer point. However uncorrelated energy transfers are produced only by UV irradiation; with ionizing radiations energy transfers occur in clusters (designated variously as blobs, spurs, δ-rays, tracks etc).

Linear energy transfer is one concept to characterize the aggregation of energy transfers, but it is in many ways a poor concept. The y-distributions afford a more realistic characterization of the spatial concentration of energy transfers. Another possibility consists in quoting an actual

parameter of correlation. The distance distribution is such a parameter of correlation. It has been given the following definition (7):

$t_D(x)\,dx$ is the expected energy imparted within a distance x to x+dx from an energy transfer randomly selected.

With no correlation this would be:

$$t_D(x) = 4\pi x^2 \rho D \qquad (1)$$

where D is the absorbed dose, and ρ is the density.

For actual particles one obtains an additional term t(x) which represents correlated energy transfers, i.e. energy transfers from the same track:

$$t_D(x) = t(x) + 4\pi x^2 \rho D \qquad (2)$$

The dose-dependent term is trivial. It is therefore sufficient to consider the function t(x) which can be used to characterize radiation quality. This function is called the *distance distribution* of energy transfers; one can show that it is in fact the (non-normalized) distribution of distances of randomly selected pairs of transfers in the same particle track. However the term *proximity function* has also been used (8).

One can also use the integral:

$$T(x) = \int_0^x t(x')\,dx' \qquad (3)$$

which is equal to the expected energy imparted in a sphere of radius x centered at a randomly selected transfer point.

Computation of t(x) *and* T(x) *from the coordinates of charged particle tracks*

For a given spatial pattern of energy transfers one can compute the corresponding functions t(x) and T(x). Since an actual pattern comprises a large but finite number of energy transfers, t(x) will be a sum of Dirac δ-distributions, and T(x) will consist of discrete steps.

Let $\Delta\varepsilon_i$ (i=1,2, ... I) be the energy transfers and let x_{ik} be the distance between the transfer points T_i and T_k. Then the formulae for t(x) and T(x) are:

$$t(x) = \sum_{i=1}^{I} \sum_{k=1}^{I} \delta(x_{ik}-x)\ \Delta\varepsilon_i\ \Delta\varepsilon_k \ /\ \sum_{i=1}^{I} \Delta\varepsilon_i \qquad (4)$$

and

$$T(x) = \sum_{i=1}^{I} \sum_{k} \Delta\varepsilon_i\ \Delta\varepsilon_k \ /\ \sum_{i=1}^{I} \Delta\varepsilon_i \qquad (5)$$

where the summation extends over all k with $x_{ik} < x$

The terms with i=k are included so that T(o) has the finite value $\overline{\Delta\varepsilon_i^2} \ /\ \overline{\Delta\varepsilon}_i$, that is the energy average of the individual energy transfers.

Fig.2 gives a schematic two-dimensional example for the calculation of the distance distribution. As will usually be the case in numerical evaluations, the δ-distributions are approximated by distributions of finite width. For simplicity the energy transfers are all taken to be of the same value; this corresponds to the case where one observes only ionizations,

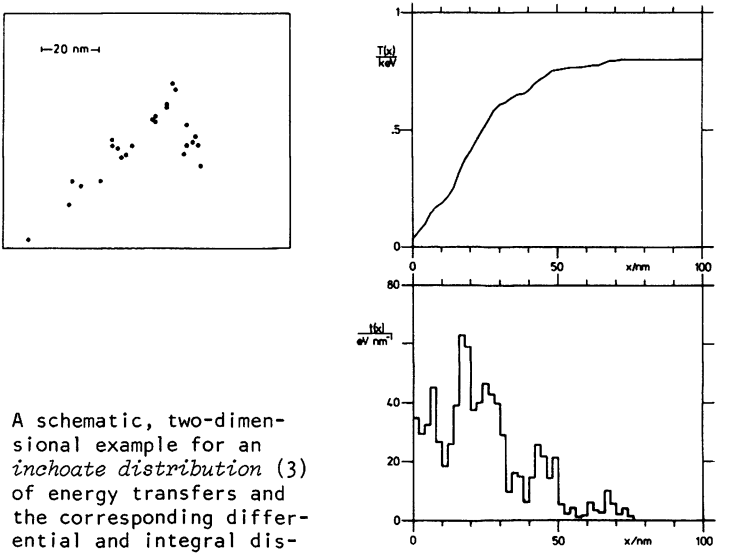


Fig.2 A schematic, two-dimensional example for an *inchoate distribution* (3) of energy transfers and the corresponding differential and integral distance distribution.

Actual distributions t(x) and T(x) belong not to one sample of a particle track but are the average obtained for many samples.

while excitations are disregarded[+)]. In actual microdosimetric computations one obtains smooth curves which are the result of the superposition of distributions belonging to many particle tracks.

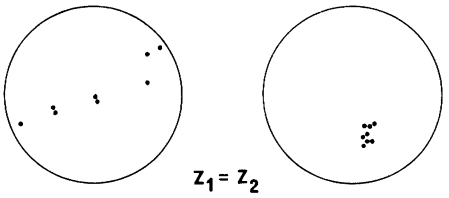
A limited number of distance distributions has been computed by several authors from simulated particle tracks (4,5,9). A systematic effort to obtain such distributions for electrons and for heavy charged particles of various energies is desirable.

Applicability of the distance distributions

An earlier theoretical treatment which has been termed the theory of dual radiation action (10) has utilized the microdosimetric quantity specific energy z. The main result of the theory is a linear-quadratic dose dependence for cellular lesions that result from the combinations of pairs of sublesions. The use of the quantity z had made it necessary in the earlier treatment to assume certain sites in the nucleus of the cell where sublesions would be produced and where they would interact with constant probability regardless of their separation. There is no experimental evidence to support such an assumption. It must instead be assumed that sublesions can be produced throughout the nucleus and that they combine with a probability that depends on their separation.

In spite of its approximate nature the earlier treatment was judged to be satisfactory for charged particles with ranges larger than or comparable to the dimensions of the nucleus. Such particles will always spread energy transfers over a large part of a specified microscopic region. Accordingly the biological effects will be similar at equal values of z; the internal distribution of energy transfers within the region will be of minor importance.

[+)] The definition of t(x) is given in a form that includes all energy transfers. It is obvious that this could be modified. If biological evidence should indicate that excitations have little or no effectiveness, one may redefine t(x) as well as ε, z, or y to refer only to ionizing interactions



3a 3b

Fig.3 An event where the same specific energy z is produced by a particle of long range (a) and a particle of short range (b)

The situation is different for particles of very short range such as the electrons from soft x-rays. As indicated in Fig.3, a narrow cluster of energy transfers may result which is substantially more effective than the same increment of z produced by long range particles. This must be so if closely neighbouring sublesions have an enhanced probability of interaction.

A recent generalization of the theory is based not on the quantity z but on the distance distributions. This generalized treatment is valid also for short-ranged particles, and it is equally applicable to studies such as the molecular ion beam experiment described by Rossi et al.(11). An explicit treatment has been given elsewhere (8), but a brief statement of the essential result will follow.

General formula for dual action

It is assumed that sublesions are produced by individual energy transfers within an extended cellular structure which may be the nucleus of the cell or a part of the nucleus. This structure is termed the *sensitive matrix*. According to this assumption the sublesions will be a subset of the energy transfers within the matrix.

It is further assumed that sublesions can combine to form lesions. The average combination probability of two sublesions separated by the distance x is denoted by g(x).

An additional postulate is that the total number of sublesions exceeds considerably the total number of lesions, i.e. it is assumed that the magnitude of g(x) is small. If this assumption is invalid, as it may be for very densely ionizing radiations, one will have to account for competition between sublesions. The interaction probability of two sublesions will then depend on the presence of other, neighbouring sublesions. This more complicated case will not be considered. It will also be assumed that either the irradiated cells are randomly oriented, or that the radiation field is isotropic.

Under these assumptions one obtains the linear-quadratic dependence of the mean number of sublesions per cell (8):

$$\epsilon(D) = k(\xi D + D^2) \qquad (6)$$

where the coefficient ξ is determined by the following equation:

$$\xi = \int_0^\infty \frac{t(x)\ g(x)\ s(x)}{4\pi x^2 \rho}\ dx \ \Big/ \ \int_0^\infty g(x)\ s(x)\ dx \qquad (7)$$

The function s(x) is entirely analogous to the function t(x). However it refers to the matrix, i.e., the sensitive structure of the cell, and not to the charged particle track. s(x)dx is the expected volume of the matrix at distance x to x+dx from a point randomly selected in the matrix. In mathematical morphology the function s(x) is called the *covariance* of a geometrical object (12,13). It depends only on the geometry of the matrix. For a sphere it is of simple analytical form (7); for other geometries it can be obtained numerically.

The general formula for ξ appears surprisingly simple in view of the fact that it accounts both for the complicated track structure and for the geometry of the matrix.

A preliminary analysis of the molecular ion experiment (14) and of experiments with low energy electrons (15,16) has led to the conclusion that sublesions can interact over distances of the order of micrometers but that there is a greatly enhanced probability for the interaction of sublesions over much closer distances of the order of 0.1 μm. This may be due to the fact that the interaction probability g(x) rises sharply at small separa-

tions x. It could also result from the fact that the matrix consists of small clusters of DNA randomly spread over larger regions of the nucleus.

The notion of intra-track dose $\Delta(x)$

Absorbed dose is defined as expected energy imparted to a region divided by the mass in this region. $t(x)/4\pi\rho x^2$ is the expected energy imparted to a spherical shell centered at a transfer point, divided by the mass of the shell. Accordingly one can consider this quantiy as a *conditional absorbed dose* in the vicinity of an energy transfer:

$$\Delta(x) = t(x) \; / \; 4\pi x^2 \rho \qquad (8)$$

This conditional dose is due to energy imparted by the same particle track; it will therefore be termed *intra-track dose*. One may note the similarity of this concept to the frequently invoked notion of a radial dose distribution around the track of heavy charged particles.Contrary to occasional criticism it is justified to apply the term dose in this context.

Fig.4 gives the functions t(x) and T(x) for different particles and Fig.5 represents the corresponding intra-track doses $\Delta(x)$. In Fig.6 the results

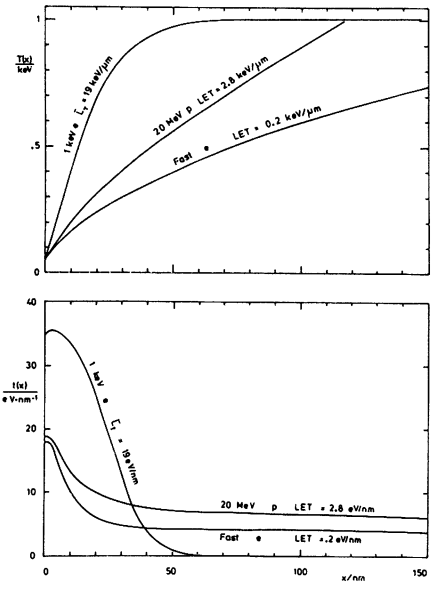
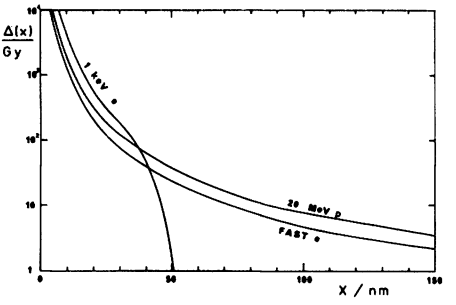


Fig.4 Differential and integral distance distributions t(x) and T(x) for 1 keV electrons (total track),for fast electrons, and for 20 MeV protons. Data from (9).

Fig.5 The intra-track dose $\Delta(x) = t(x)/4\pi x^2\rho$ corresponding to the data in Fig.4



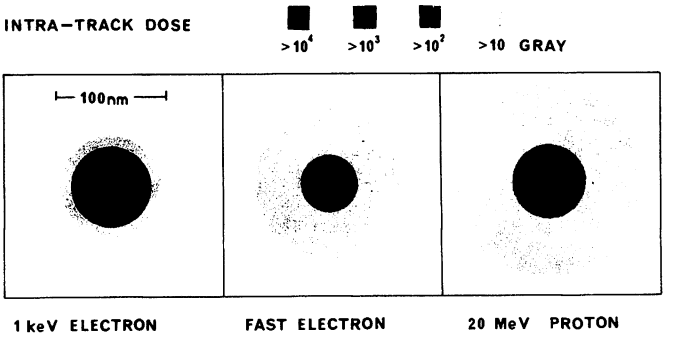


Fig.6 Schematic representation of the spatial distribution of intra-track dose, i.e., the data from Fig.5 in the form of an iso-$\Delta(x)$ diagram.

are given in a more illustrative,schematic form. The biophysical implications are readily apparent. The intra-track dose in the close vicinity of an energy transfer is large even for sparsely ionizing radiations. At absorbed doses of a few hundred rad it is therefore very likely that the neighbours of an energy transfer, (or of a sublesion) belong to the same particle track; it is very unlikely that they belong to independant particle tracks. This must be so because the frequency y of neighbouring energy transfers from the same track is proportional to the intra-track dose $\Delta(x)$, while the frequency of energy transfers from other tracks is proportional to absorbed dose D. The linear term in the dose relation must therefore exceed the quadratic term whenever $\Delta(x)$ exceeds D.

A comparison of the data given in Figs.4 to 6 for the three different radiations brings out characteristic differences. In particular, one realizes that for small separations the intra-track dose is largest for the 1 keV electron (*track ends*), while for larger separations (x>50nm) it is smaller and even approaches zero.

One may consider the hypothetical case where two sublesions are always produced at a separation a. The dose dependence of lesions is then:

$$\epsilon(D) = k(\Delta(a)\ D + D^2) \qquad (9)$$

This is readily derived from Eq(7) with $s(x) \sim \delta(a-x)$.

Furthermore one concludes from Eq(7) that ξ will always exceed $\Delta(a)$ if the linear dimensions of the matrix are smaller than a or if the maximum interaction distance of sublesions is smaller than a. The intra-track dose $\Delta(a)$ provides therefore a lower limit for the quantity ξ. This applies regardless of the complexities of track structure and the geometry of the sensitive cell organelles.

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