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THEORY OF WALL-EFFECTS IN MICRODOSIMETRIC MEASUREMENTS*

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Abstract

THEORY OF WALL-EFFECTS IN MICRODOSIMETRIC MEASUREMENTS.

Microdosimetric data and the experimental assessment of radiation quality are based upon measurements with proportional counters. The simulation of microscopic tissue regions by cavities filled with tissue equivalent gas is, however, limited by the fact that scaling relations are not preserved when a particle track has multiple intersections with a boundary between regions of different density. This limitation has forced various attempts to replace conventional proportional counters with wall-less constructions. In spite of its practical importance to microdosimetry there is as yet no satisfactory analysis of the problem. General theorems which allow a quantitative determination of the wall-effects can, however, be derived. First one can extend Fano's theorem from a statement on the fluence spectrum at a point to a statement on the spectrum of track segments in extended domains. As a second step one can then evaluate those changes in the statistical correlation of track segments which are brought about by density variations in the irradiated medium. Finally one can give a generalization of Cauchy's theorem on the mean chord length in convex bodies to curved and finite tracks and their secondaries. These results make it possible to assess the differences between energy deposition spectra in conventional counters and wall-less instruments.

1. INTRODUCTION

An increasing number of studies on radiation quality is being based on microdosimetric concepts and quantities. While microdosimetry has developed into an efficient tool of radiobiology, one aspect has, however, remained largely unresolved. This is the problem of the so-called wall-effects. Wall effects are distortions in the statistics of energy deposition which occur if microscopic tissue regions are simulated by gas-filled cavities. Rossi and his co-workers have drawn attention to these distortions early in the development of microdosimetry (1,2); subsequently wall-less proportional counters have been constructed in order to overcome the effect in microdosimetric measurements (3,4,5,6).

This paper contains a synopsis of relevant concepts and of geometrical theorems which are useful as a basis for a theory of wall effects. Such a theory is desirable because criteria are needed to decide whether in any particular case conventional proportional counters are applicable, or wall-less instruments must be used.

In order to give a brief survey it will be necessary to draw together results without detailed derivations. Proof of the various relations are given in more technical investigations (7,8).

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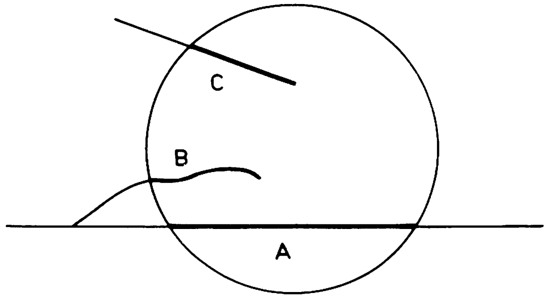

FIG. 1. Definition of the concept track segment.

2. CHARACTERIZATION OF WALL EFFECTS

2.1 Definition of Concepts

Several concepts will be needed throughout the discussion. The first concept is that of an energy deposition event. The term signifies energy deposition in the region, U, of interest by a charged particle and/or its secondaries. An event can also involve two charged particles set in motion by the same uncharged particle. Two energy depositions belong to different events if they are statistically independent, that is if they cannot be traced back to a common quantum act. The term event will be used in a somewhat more general connotation which also includes passage of a charged particle without actual energy deposition in U. The distinction can be neglected except for very small regions and sparsely ionizing particles.

A charged particle track is the line of motion of a charged particle together with the branches and subbranches formed by its secondaries. Track length is the total length of the track including its branches. A track segment is a continuous portion of a track lying inside the region, U. Two segments may belong to the same track, as for example the segments A and B in Fig.1.

Event multiplicity, M, is the mean number of segments per event in U. If the frequency of segments in U per unit dose is Φ_s and Φ is the frequency of events, then the multiplicity is:

$$M = \Phi_s/\Phi \tag{1}$$

2.2 Types of Wall Effects

Wall effects are due to the fact that the cavity filled with low density gas is surrounded by high density material. In the walls the charged particle tracks are short as compared to the dimensions of the cavity.[1] The boundary of the cavity as seen from the outside of the cavity then appears as a plane. This leads to the fact that track segments can occur simultaneously which would in the standard case

[1]With the commonly employed cavity sizes the condition holds for electrons up to 1 MeV and for heavier particles of much higher energy. Other cases are excluded from this discussion.

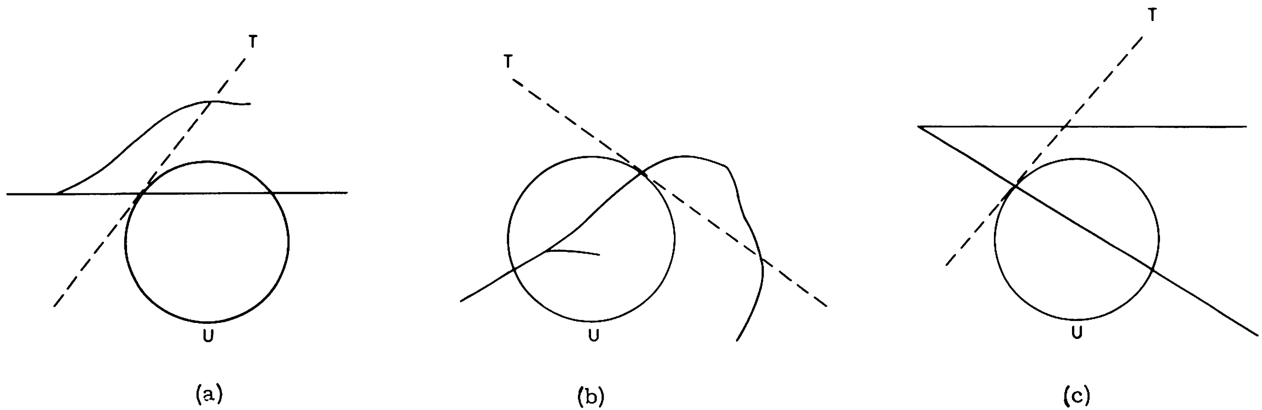

FIG. 2. Scheme of three types of wall-effects.
(a) delta-ray effect
(b) re-entry effect
(c) V-effect

(i.e., when the region U is surrounded by material of the same density) be statistically independent. Three principal processes can be distinguished.

In the standard case a primary particle may traverse U while a δ ray formed outside U does not enter the region but traverses the plane, T, which is tangential to U at the entrance point of the primary particle. In the cavity case traversal of the tangential plane, T, means entrance into the cavity. The situation is schematically represented in Fig.2a. The simultaneous entrance of the primary and the secondary particle is called delta ray effect.

A similar process is represented in Fig.2b. The effect is due to the back scattering of the charged particle after it has traversed the cavity. This re-entry effect is significant only for electrons with their curled tracks.

A third type of wall effect is the V-effect. This effect is represented in Fig.2c. The V-shaped track of two nuclear fragments formed in a nonelastic nuclear collision has a higher probability for simultaneous passages through the cavity than through the actual microscopic region.

2.3 Increase of Multiplicity

A common characteristic of the different types of wall effects is that they increase event multiplicity. The shape and the relative frequency of track segments in the region, U, is not affected by the density of the walls; this is true under the conditions of Fano's theorem (9), and it follows from this theorem. It is merely the statistical coupling between segments which depends on the density of the material surrounding U.

Assume that the region U is convex. Then one obtains multiplicity 1 in the free space case, i.e., when U is positioned in vacuo. In the standard case the multiplicity is near 1, if one deals with small regions. In the cavity case one has maximal multiplicity. Estimates of the numerical values are given in section 3.

2.4 Event Frequency and Mean Event Size

If a convex region of volume V and surface S is randomly traversed by infinite straight lines (Fig.3a), then the mean chord length, $\bar{\ell}$, in the region is equal to 4V/S. This is the so-called theorem of Cauchy. If the tracks are finite and of mean range $\bar{r}$, then one can show that the mean segment length in the region is:

$$\bar{s} = (1/\bar{\ell} + 1/\bar{r})^{-1} \qquad (2)$$

This is the generalization of Cauchy's theorem to the situation represented in Fig.3b. The generalization goes, however, further than that. Eq. (2) holds even in the case where one deals with an isotropic field of tracks which are curled and branched (10). This complete generalization is indicated in Fig.3c. The quantity $\bar{\ell}$ is equal to 4V/S, the mean range is the mean length of tracks including their branches, and $\bar{s}$ is the mean length of segments as defined in 2.1.

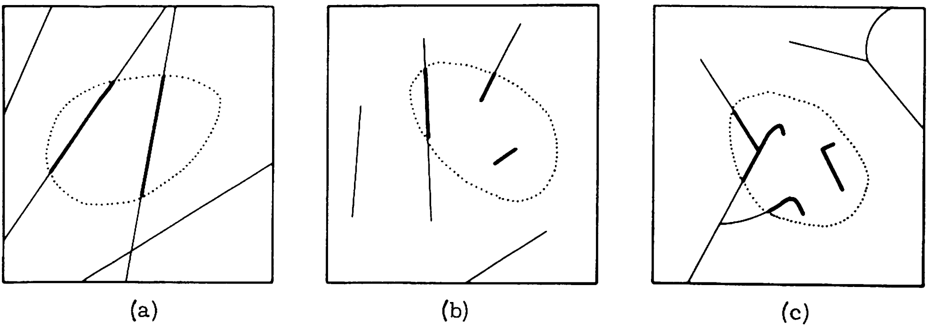

FIG. 3. Diagram for the Cauchy theorem and its generalizations.
(a) Infinite, straight random tracks
(b) Finite, straight random tracks
(c) Finite, curved, and branched random tracks

The general Cauchy theorem leads to the following formula for the segment frequency per rad:

$$\Phi_s = .062\ (1 + \bar{r}/\bar{\ell})\ V/\bar{E}_o \tag{3}$$

$\bar{E}_o$ (keV) is the mean initial energy of the charged primaries, $\bar{r}$ their mean track length including delta rays. V(μm^3) is the volume of the region, and it is assumed that this region has density 1.

Φ_s is equal to the event frequency for the free space case. For small regions it is also nearly equal to the event frequency in the standard case. In the cavity case it can be markedly larger than the event frequency, and one must divide it by the appropriate multiplicity to obtain the event frequency or its inverse, the mean event size.

3. NUMERICAL ESTIMATES

3.1 Heavy Particles

The δ rays of heavy charged particles are short as compared to the length of the primary track. Therefore the probability is very small that a δ ray enters the cavity while the primary track does not enter it. Consequently the indirect events, i.e., those events where the primary particle passes outside the region, U, and merely injects one or several of its δ rays into U are suppressed in the cavity case. If t_δ/t_p is the δ ray track length per unit primary track length then the multiplicity is:

$$M = 1 + t_\delta/t_p \tag{4}$$

The very short δ rays lead to double events even in the standard case. In order to obtain an estimate of the wall effects one must therefore exclude these short δ rays from t_δ. A reasonable approximation is to exclude all δ rays whose range is less than the equivalent diameter of the region U.

Table I gives the δ ray length per unit primary track length for protons at various energies. The multiplicity increase due to the

TABLE I. DELTA RAY RANGE PER UNIT LENGTH OF PRIMARY TRACK

Proton energy (MeV)	All δ rays	δ rays > .1 μm	δ rays > 1 μm
2	0.48	0.20	--
5	0.33	0.22	0.10
10	0.26	0.20	0.14
20	0.21	0.18	0.15
50	0.17	0.16	0.15
100	0.15	0.14	0.13

δ ray effect is of the order of .15 in the typical case of an equivalent diameter of 1 μm; i.e. about 15% of all pulses observed in a conventional tissue equivalent proportional counter are too large due to δ ray influx. The event frequency is reduced by about 15% and the mean event size is increased correspondingly.

The suppressed indirect events are on the average much smaller than the direct events (4). The fraction of energy involved in the distortion is therefore significantly smaller than 15%. Numerical values for charged particles and for neutron fields are given in ref. (8).

For heavier particles of atomic number Z at given energy per nucleon one has to multiply the values in Table I by Z^2. This means that most of the events can be distorted due to the δ ray effect. The fraction of energy involved in the distortions is, however, the same as that for protons.

The V-effect can be an appreciable part of the wall effects, if the neutrons or charged particles have enough energy that a significant part of the absorbed dose is produced by nonelastic nuclear collisions. Numerical analysis has to be based on the nuclear cross sections in each particular case. The probability that an event produced in a cavity by a V-shaped track is a double event is given by the formula:

$$P = \frac{L-c}{L+c} \qquad (5)$$

where L is the combined length of the two arms of the track and c is the distance of the two terminal points (see ref. (7)). The V-effect is small for neutrons below 10 MeV, and for heavy charged particles of considerably higher energy.

3.2 Electrons, x Rays, and γ Rays

Electrons have a much smaller δ ray track length per unit length of primary track than heavy charged particles. Between 10 kV and 1 MeV the value 0.06 is never exceeded. Between 100 and 300 keV the value is near 0.03 (see (7)). The δ ray effect is therefore small for electrons, x rays and γ rays.

Approximately 20% of all events in a conventional counter are, however, double events due to the backscattering of the primary electron. This follows from the fact that the Albedo, R, properly averaged over all angles, lies between .25 and .20 for electrons from 2 keV to 1 MeV (11).

One can also show that the fraction of returning electrons is bracketed by the following equation:

$$\frac{r - r_o}{2\,r} < R < \frac{r - r_o}{r} \qquad (6)$$

where r is the integrated range of the electron without δ rays and r_o is the distance between the starting point and the end point of the track (7). This relation agrees with the calculated Albedo values, and confirms that the re-entry effect is dominant for electrons.

Pair production can further contribute to the wall effects. Due to their curved tracks the two electrons can simultaneously traverse the cavity in spite of the fact that they start out diametrically.

3.3 Requirements for Wall-less Configurations

Wall-less proportional counters work on the principle that the sensitive region U_1 of diameter d_1 is positioned in the center of a cavity U_2 of larger diameter, d_2. In such a configuration only δ rays of range exceeding $(d_2-d_1)/2$ can be involved in wall effects. However simultaneous events can still occur due to long range δ rays, due to electron re-entry, and due to the V-effect. The following relation is useful for an estimate of the extant effects.

If a convex body, U_1, of surface S_1 is situated inside a convex body, U_2, of surface S_2 then the fraction S_1/S_2 of all random chords traversing U_2 pass through U_1. This can be shown on the basis of formulae on the random traversal of convex bodies (10).

The relation implies that the extent of the wall effects decreases by the factor $(d_2/d_1)^2$ for all those double events in which the angle of entrance of simultaneous segments is uncorrelated.

For electron backscatter this is a conservative estimate because re-entry is most likely for those electrons which leave the surface of U_2 under a small angle, and most of the re-entering electrons re-enter under a small angle. A ratio, d_2/d_1, of 4 will therefore decrease the percentage of simultaneous events due to electron re-entry to well below 1%.

On the other hand it must be assumed that the most energetic δ rays run nearly parallel to the primary track at least in the initial parts of their track. The probability of simultaneous events due to these δ rays will then decrease by less than the factor $(d_2/d_1)^2$.

Relativistic heavy nuclei can produce spallation showers which are sharply bundled forward. In this case one would have to have a ratio d_1/d_2 much smaller than the angle between the nuclear fragments in the bundle if simultaneous events were to be suppressed. This may lead to prohibitive values of d_2/d_1.

ACKNOWLEDGEMENTS

The author is greatly indebted to Dr. H.H. Rossi and Dr. W. Gross for frequent discussions and for many valuable suggestions.

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DISCUSSION

V.I. IVANOV: Both yourself and Mr. Katz (in paper IAEA-SM-145/9) [1] mentioned dose distribution in the track. What does "dose" signify in this case?

A.M. KELLERER: Absorbed dose is always an expectation value. I would therefore be hesitant to speak about absorbed dose in a track. Microdosimetry distinguishes between the stochastic quantity of specific energy and the non-stochastic quantity of absorbed dose. The absorbed dose, D, can be defined as the expectation value of the specific energy, Z. In this sense one may talk about a dose profile around a track; it is an idealized profile, obtained when the particle passage is repeated very often.

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[1] These Proceedings.

For a rigorous definition given, for example, in the ICRU report on Quantities and Units, one must include a limit process by reducing to zero the volume V in which Z is measured:

$$D = \lim_{V \to 0} \bar{Z}$$

H. H. EISENLOHR: I wonder how general the generalized Cauchy theorem is? Is there, for instance, any restriction imposed on the angle by which the particle is bent inside the volume?

A. M. KELLERER: The theorem is valid for arbitrary shapes of the track and for regions which need not be convex. The sole condition is that the particle fluence is uniform and isotropic.

R. KATZ: What are your future plans for generating survival curves from microdosimetric theory?

A. M. KELLERER: We feel that generating survival curves and curve fitting techniques are limited by the fact that survival curves are in general the complex result of several different stochastic factors. The statistics of energy deposition is only one of these factors. One cannot therefore expect that equations based on this single factor will lead to valid conclusions on the primary mechanisms of radiation action. We try to apply microdosimetric reasoning in a general way in order to obtain numbers of interacting absorption events and their interaction distances. In another paper (IAEA-SM-145/10)[2] Mr. Rossi will present details and results.

[2] These Proceedings.