Influence of Sensitive Volume Dimensions on the Distribution of Energy Transferred by Charged Particles

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Abstract. The most of radiobiological effects are initiated by energy deposition events in nanometer sized cellular structures like DNA, nucleosome etc. Therefore it is necessary to investigate the distribution of energy deposited in a sensitive volume of nanometer dimensions. An experimental measurement of the deposited energy distribution with good space resolution is very difficult, especially in time corresponding to physical stage of energy deposition. Computer simulations enable to calculate the incident space distributions of deposited energy, retaining internal stochastic nature of events taking place at a particle track formation. The distribution of energy deposited in a sensitive volume of micro- or nanometer scale depends on a dimension and shape of volume taken into account. In a case that this volume represents a sensitive volume of a detector, the detector response can vary for the same radiation as a function of dimensions mentioned. Presented work deals with theoretical analysis of deposited energy distribution as a function of sensitive volume dimensions. As an input data are used data acquired in track simulations performed by means of the code TRIOL. The Monte Carlo code TRIOL includes for modelling of energy deposition in liquid water all main interaction processes including ionization of outer shells, oxygen K-shell ionization, excitations, and elastic scattering of electrons. The results for 1 MeV electrons as the charged particles with low linear energy transfer, 1 and 10 MeV protons, and 5.5 and 50 MeV alpha particles as a representative of heavier charged particles are presented. The calculations are performed for spherical sites of 3, 30, and 1000 nm diameters. It is found that the distributions of transferred energy actually vary with dimensions in a lesser extent than expected. Conclusions for responses of some experimental microdosimetry methods are formulated.

1. Introduction

The distribution of the energy deposited by ionizing radiation in a sensitive volume on the micro- or nanometer scale can depend on the dimension of this volume. When the volume represents a sensitive structure of a detector, the mentioned distribution can influence in an important way the response of such detector to different particles and/or radiation, following their characteristics.

It was estimated, for example, that the sensitive volumes of some of experimental microdosimetry methods differ in a large extent:

- the sensitive volume of a microdosimetry tissue equivalent proportional counter (TEPC) has the dimensions of the order of few µm [1];
- the critical volume of so-called bubble detectors (BD) would be of the order of few tens of nm [2]; and
- the critical region for the track appearance in the track etched detectors (TED) was appreciated to be of the order of few nm [3].

The responses of these methods could therefore vary due to the differences in sensitive (critical) volume dimensions. To analyse this possibility also theoretically, the distributions of energy transferred as a function of the critical volume dimensions were calculated. This report describes the results obtained.
2. Materials and Methods

2.1. Track structure modelling

Particle track structures, which are the basic data necessary for calculations, are obtained using the program package TRIOL [4-6]. The Monte Carlo code TRIOL takes into account for modelling of energy deposition in liquid water all main interaction processes including ionization of outer shells, oxygen K-shell ionization, excitations, and elastic scattering of electrons. The spatial coordinates of all energy deposition events of a primary particle and its secondaries are recorded together with the type of interaction and the amount of deposited energy.

2.2. Calculation of energy distributions

Track structures obtained with the code TRIOL for chosen types and energies of ionizing radiation are used as an input data for calculations of energy distributions. The defined testing volume of spherical geometry is randomly placed in the proximity of a track and an energy deposited within the volume is calculated. In order to obtain reasonable statistical error of results, it is necessary to have a significant number of spheres with nonzero deposited energy. However, if the critical volume would be placed fully arbitrarily, it would contain an energy deposition event very rarely and the computing time would be very long. For these reasons the calculation procedure is set up as following:

- random deposition event is chosen within a track and its coordinates are taken as a starting point;
- the starting point is shifted in random direction by a distance lower or equal the radius of the considered testing sphere;
- the sum of energies for all energy deposition events located within testing sphere is calculated and recorded.

In such a way, the full distribution of transferred energy is calculated. The calculation can be stopped in any instant, but we tried to gather as good statistics as possible. At least $10^5$ of hinted volumes per track were taken into account to obtain the distributions presented further.

2.3. Particle’s choice

In a mixed radiation field many different charged particles contribute to the energy deposition. To obtain the most relevant estimation, the basic contributing particles are taken into account: electrons representing the charged particles with low linear energy transfer; protons representing the most of energy deposition events characteristic for mixed radiation fields encountered, and alpha particles as a representative of heavier charged particles.

The energies of primary particles were chosen in such a way to cover the region of stopping power up to about 100 keV/µm. Only results for 1 MeV electrons, 1 and 10 MeV protons and 5.5 and 50 MeV alpha particles are shown in the paper. The calculations were performed for track sections 100 keV of deposited energy by primary particle.

3. Results

Typical distributions of energy transferred by different charged particles as a function of the diameter of a critical volume are presented in Figs. 1 to 5. The deposited energy distribution is shown as a function of lineal energy $y$ in form $y.d(y)$. 
**FIG. 1.** Distributions of energy transferred in a tissue spherical volume by 1 MeV electrons.

**FIG. 2.** Distributions of energy transferred in a tissue spherical volume by 1 MeV protons.
FIG. 3. Distributions of energy transferred in a tissue spherical volume by 10 MeV protons.

FIG. 4. Distributions of energy transferred in a tissue spherical volume by 5.5 MeV alpha particles.
FIG. 5. Distributions of energy transferred in a tissue spherical volume by 50 MeV alpha particles.

The values of stopping power in human tissue for heavier charged particles are presented in the Table I together with average values of deposited energy calculated from the distributions in Figs. 1 to 5.

Table I. Stopping power and deposited energy in wet human tissue for some charged particles.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy [MeV]</th>
<th>Stopping power [keV/μm] [7]</th>
<th>Average lineal energy [keV/μm] deposited in sphere with diameter of 3 nm</th>
<th>30 nm</th>
<th>1000 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>1</td>
<td>0.2</td>
<td>12.6</td>
<td>4.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Protons</td>
<td>1</td>
<td>26.0</td>
<td>18.5</td>
<td>12.7</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4.6</td>
<td>13.3</td>
<td>5.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Alpha particles</td>
<td>5.5</td>
<td>82.6</td>
<td>33.0</td>
<td>31.3</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>15.1</td>
<td>15.2</td>
<td>8.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

When comparing the values in the Table I and the graphical dependencies in Figs. 1-5, several conclusions can be drawn:

1. The energy distributions are well situated close to the region of the stopping power’s values. As expected they are generally larger when the critical volume dimensions decreases.
2. There are only small differences in the energy distributions for the critical volumes with radii of 3 and 30 nm in contrast to results for the sphere of 1000 nm.
3. As far as the 1000 nm large site is concerned, the main difference consists in much narrower energy distributions, the most probable values of deposited energy are generally shifted bellow the value of the linear energy transfer.
4. Discussion

As it was stated, the theoretical analysis presented in this report was performed with the goal to estimate to what extent the microdosimetry spectra obtained by means of experimental methods mentioned in the Introduction can possibly reveal the differences in the microdosimetry distributions of the transferred energy. Following conclusions can be drawn from the results of theoretical calculations in this context:

1. It was found that the calculated deposited energy densities do not reflect exactly the concept of the linear energy transfer and further analysis of obtained data is necessary.
2. It cannot be expected that the microdosimetry spectra obtained with the TED and/or sets of bubble detectors will significantly differ. For the dimensions of theirs critical volumes (several nm for TED, few tens of nm for BD) the distributions of energy transferred are rather similar.
3. Theoretical calculations do not permit to clearly predict whether and to what extent the microdosimetry spectra obtained with a TEPC and with a spectrometer based on the TED can be different. Theoretical distributions of transferred energy are, when compared to the single value of LET, very large. The most probable and the maximum values of energy density are factors responsible for differences observed in experimental microdosimetric spectra.

It should be stressed that some influence of experimental methods themselves on the microdosimetry spectra cannot be excluded. The influence of short-range particles and the wall effect should be reminded in this context for the TEPC. As far as the TED LET spectrometer is concerned, the influence of the depth of etching (i.e. of the thickness of the layer removed by etching) cannot be neglected. These effects, however, cannot be taken into account in presented theoretical analysis of charged particle tracks.

References