Comparison of microdosimetric simulations using PENELOPE and PITS for a 25 keV electron microbeam in water

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Abstract

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The calculations presented compare the performances of two Monte Carlo codes used for the estimation of microdosimetric quantities: Positive Ion Track Structure code (PITS)[1–3] and a main user-code based on the PENetration and Energy LOss of Positrons and Electrons code (PENELOPE-2000)[4,5]. Event by event track-structure codes like PITS are considered superior for microdosimetric applications and they are written for this purpose. PITS tracks electrons in water down to 10 eV. PENELOPE is one of the few, among widely available general purpose codes, that can simulate random electron-photon showers in any material for energies from 100eV to 1GeV.

The model for the comparison is a large water cylinder with an internal scoring geometry of spheres with 1μm diameter where the scoring quantities are calculated. The source is a 25 keV electron pencil beam impinging normally on the sphere surface. This work shows only the lineal energy as a function of position and lineal energy spectra at a given location since for microdosimetry and biology applications, and for discussion of radiation quality in general, these answers are more appropriate [6–9]. The computed PENELOPE results are in agreement with those obtained with the PITS code and previously published in this journal [3]. This paper demonstrates PENELOPE's usefulness at low energies and for small geometries. What is still needed are experimental results to confirm these analyses.

Key words: Electron and photon transport, Monte Carlo codes, microdosimetry, electron microbeams, bystander effect, single cell

Introduction

The purpose of this computational work was to support an ongoing experimental program at the Advanced Light Source (ALS) synchrotron facility at LBNL. These calculations are intended to support basic research into what is referred to as the "bystander effect" for low doses of radiation in very small volumes of biologically-important materials.
"Bystander effect" refers to a wide range of effects on unirradiated cells from radiation-exposed neighbors [10–16]. Although the mechanisms underlying bystander effects are unknown, multicellular crosstalk following exposure to low doses or low-dose rates of ionizing radiations may trigger signal transduction pathways that might deregulate normal cell function in the irradiated, as well as neighboring unirradiated cells, leading to bystander effects. It is essential that the microdosimetry of microbeams of low-LET and high-LET radiation be completely characterized in order to elucidate bystander mechanisms.
Event by event track-structure codes like PITS are believed to be superior for biological and microdosimetric applications and they are written for this purpose. On the other hand these codes are not always available to the general public for simulations with different goals in mind from the ones for which they were created. A list of track-structure codes with their main differences have been made by Nikjoo et al.[17,18].
PENELOPE is one of the few, among widely available general purpose codes, that can simulate random electron-photon showers in any material for energies from 100eV to 1GeV. Moreover this code can be adapted to the user's goal, for example in biological and microdosimetric applications although not much work has been done to verify the applicability of the code to these kinds of purposes.
The purpose of our preliminary computational work is to verify that the PENELOPE code can be applied to aid investigations of bystander effects in individual cells due to x-ray microbeams.
This work has entailed the application of two different Monte Carlo codes to calculate various microdosimetric quantities in water referring to some published results, although little experimental and computational work exists for electron and photon microbeams for energies below 25keV. One recent publication with results from the PITS track structure code [1–3] was presented by W.Wilson [3].

Method of calculation

The overall model for the comparison presented in this paper is a water cylinder of 10μm radius and 1μm height with an internal scoring geometry made of

spheres with 1μm diameter. The source is a pencil electron beam of energy 25 keV impinging the cylinder along its axis and normally on the sphere surface. This was done considering that the radiation field is rotationally symmetrical about the beam axis. This allows one to choose equivalent non-overlapping spherical scoring sites with the centers at a constant radial distance r from the axis with r from 0 to 10μm and at the fixed penetration distance x=1μm. Published results obtained with PITS [3] refer to a cylindrical geometry that is 10μm height, 10μm radius and filled with 1μm spheres; the focus of the calculations presented in this paper has been only on the first layer of spheres having their centers at depth 0.5μm. Other more extensive work has been produced and published as an internal report [1] [2] [3]. Logarithmically distributed energy bin widths were used in scoring energy deposited in each sphere with both codes. Results with PENELOPE have 100 bins while PITS results presented in [3] have 40 bins. Using 40 bins does not produce a difference in the shape of the spectra.

PENELOPE simulates electron-positron-photon transport in up to 92 elements and in 180 compounds and mixtures. Several subroutines need to be compiled and linked with a main program provided by the user; this main user-code has to control the evolution of the simulated tracks, keep score of the relevant quantities and define the material, volume, internal scoring volumes. The PENELOPE code is written in FORTRAN77 while the user-code is written in both FORTRAN77 and Matlab. Both the code and the user-code are compiled and run on a 650Mhz PC. Using PENELOPE 200,000 Monte Carlo histories were simulated in about one hour computer time. The statistical standard deviation of the results is always kept lower than 1%.

With PITS up to 200,000 tracks were simulated while no accounting was kept of the computer time necessary to complete the simulation. The total computer time involved amounted to hundreds of hours on dedicated workstations. The difference in computer time is explained with the different simulation algorithm. Codes like PITS deal with event-by-event simulations using a detailed-history Monte Carlo method and track electrons down to 10 eV based on measured cross-sections for electron scattering from water molecules. [1,2] PENELOPE, on the other hand, uses an algorithm that incorporates a scattering model that combines numerical total cross sections (or stopping cross sections) with simple analytical differential cross sections for the different in-

[1] LBNL Report 51487. E. Mainardi, R. J. Donahue, E. A. Blakely. PENELOPE Monte Carlo microdosimetric calculations for 25 keV electrons microbeam in water. *Lawrence Berkeley National Laboratory* **51487**, (September 2003).

[2] LBNL Report 50863. E. Mainardi, R. J. Donahue, E. A. Blakely. Comparative Dosimetric Estimates of a 25 keV Electron Microbeam with Three Monte Carlo Codes. *Lawrence Berkeley National Laboratory* **50863**, (September 2002).

[3] LBNL Report 53629. E. Mainardi, R. J. Donahue, E. A. Blakely. A user-code for Photons and Electrons Microdosimetry. *Lawrence Berkeley National Laboratory* **53629**.

teraction mechanisms. Individual interaction events are simulated by means of purely analytical, exact sampling methods, so that the structure of the simulation code is very simple. For electron transport PENELOPE implements a "mixed" simulation scheme that combines the detailed simulation of hard events with a condensed simulation of soft events. Events with polar scattering angle θ or energy loss W larger than previously selected cutoff values θ_s and W_c ($\theta > \theta_s$ or $W > W_c$) are treated in a detailed way. Electron transport is also characterized by many small events with scattering angle or energy loss less than the corresponding cut-offs ($\theta < \theta_s$ or $W < W_c$) that are described by means of multiple scattering approaches in a condensed simulation. With PENELOPE it is necessary to adjust to the small geometries (if compared with macroscopic problems) varying the value of DSMAX that defines the maximum allowed electron step length. When the particle moves in a thin body like the cell of our case the DSMAX was given a value of the order of one tenth of the 'thickness' of that body (0.1μm= 1/10 of layer thickness).

Results

Microdosimetry is defined as the study of energy deposition processes in biological media with particular emphasis on phenomena correlated with the physical aspects of the radiation action on living systems. Important quantities defined in microdosimetry and fully described in ICRU REPORT 36 [6] are: energy imparted ϵ, lineal energy y.
The energy imparted ϵ to the matter in a volume (scoring volume) is:

$$\epsilon = \sum_i \epsilon_i = \sum_i (T_{in} - T_{out} + Q_{\Delta m}) \tag{1}$$

where: ϵ = summation performed over all energy deposits in each sphere expressed in terms of joule (J) or eV; T_{in} = energy of the incident ionizing particle; T_{out} = sum of the energies of all ionizing particles leaving the interaction; $Q_{\Delta m}$ = changes of the rest mass energy of the atom and all particles involved in the interaction.
The lineal energy y is the energy imparted to matter in a volume by a single energy-deposit event divided by the mean cord length $\overline{l}$ in that volume and it is expressed in terms of J/m or in keV/μm: $y = \epsilon/\overline{l}$. Since the scoring volume is a sphere with diameter d=1μm, than $\overline{l} = 2d/3 = 2/3\mu$m
The quantities here presented provide a basis for understanding the results and microdosimetric quantities analyzed below. Also other microdosimetric

quantities are computed and presented in an internal report [4].

Figure 1 shows the frequency-mean lineal energy radial distribution for spheres with centers at a depth of 0.5μm and at a radial distance r from 0 to 10μm in the first layer of spheres (0-1μm). The PITS data were presented in paper [3] Figure 3 by Wilson together with data for the other depth values. As explained in the previous section this work refers only to the first layer of spheres (0-1μm). The quantity here analyzed for each sphere is:

$$\overline{y}_{Fs} = \int_0^\infty y f(y) dy \tag{2}$$

f(y) is a density distribution function with dimensions of 1/y (μm/keV) such that the probability of having an event in the interval y, y+dy is f(y)dy. The frequency-mean lineal energy radial distribution plot (Figure 1) shows the statistical fluctuations of earlier work by PITS that was overcome in later computations increasing the number of simulated tracks and consequently computer time. Nevertheless the trend of the values obtained with the two codes seems to be in quite good agreement.

[4] LBNL Report 51487. E. Mainardi, R. J. Donahue, E. A. Blakely. PENELOPE Monte Carlo microdosimetric calculations for 25 keV electrons microbeam in water. *Lawrence Berkeley National Laboratory* **51487**, (September 2003).

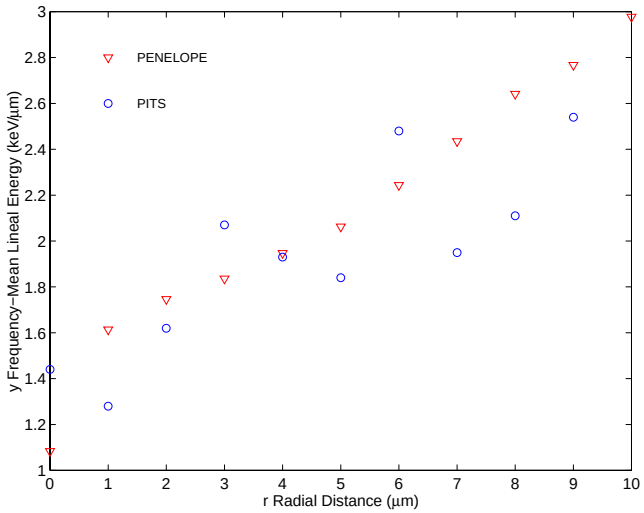

Fig. 1. Frequency-mean lineal energy radial distribution for a 25 keV electron microbeam in water. PITS data presented in [3] Figure 3 but only for the first layer of spheres (0-1μm).

Figure 2 shows the lineal energy radial distribution for spheres at radial distances r from 0 to 10μm in the first layer of spheres (0-1μm). It presents a comparison of the PENELOPE user-code with data obtained with more recent PITS simulations by W.Wilson (private communication). The quantity here analyzed is obtained for each sphere s from 1 to 11 by multiplying the frequency-mean lineal energy $\overline{y}_{Fs}$ by the probability of that sphere being hit by radiation $Phit_s$:

$$Y_s = \overline{y}_{Fs} \cdot Phit_s \tag{3}$$

$$Phit_s = \int_{\epsilon>0}^{\infty} f(\epsilon) d\epsilon \tag{4}$$

For most spheres, the agreement of results between the two codes is good, particularly for the fifth sphere (s=5, radius r=4μm and depth x=0.5μm). Nevertheless some results show relevant discrepancies especially for the first sphere (s=1, radius r=0μm and depth x=0.5μm) hit by radiation (Figure 2). The same considerations apply also for the dose values D_s (in Gy) since they are scalable from the corresponding lineal energy values Y_s (in keV/μm) by a constant and using the conversion factor $1.602 \cdot 10^{-19}$ (J/eV) for each sphere s from 1 to 11:

$$D_s = Y_s \cdot \overline{l}/mass = Y_s \cdot \overline{l}/V \cdot \rho = Y_s \cdot 4 \cdot 1.602 \cdot 10^{-1}/\pi \tag{5}$$

Plot of radial dose distribution and other computed microdosimetric quantities are fully presented in an internal report [5] .

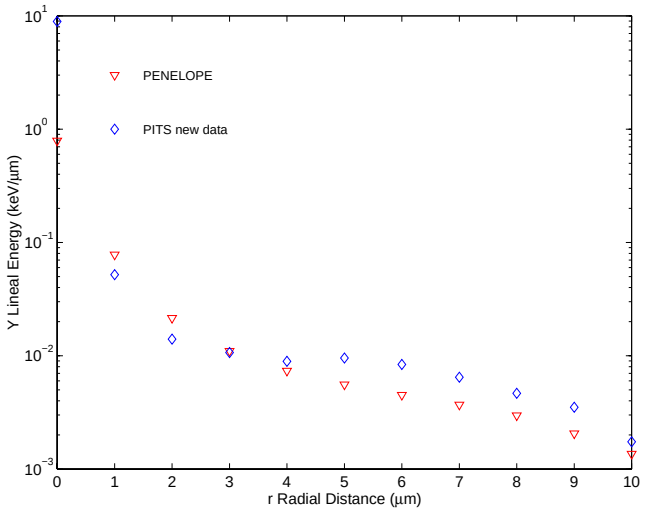

Fig. 2. Lineal energy radial distribution for a 25 keV electron microbeam in water. PITS more recent data (unpublished) for the first layer of spheres (0-1μm).

Figures 3 and 4 show the normalized frequency distribution, i.e. conditional on an event occurring in the site in lineal energy y on a semi-logarithmic scale for the first sphere hit by the micro-beam at radius r=0μm and depth x=0.5μm:

$$yf(y)vs.log(y) \tag{6}$$

This is the standard representation of a microdosimetric spectrum[7].
Figure 3 presents a comparison of the PENELOPE user-code with data obtained with PITS and presented in paper [3] Figure 5b by W.Wilson. The comparison is obtained by normalizing PENELOPE to PITS results in order to have the same area and study the shape of the spectra. The plot shows that for this radiation and for this 1μm diameter of the spherical scoring volume most microdosimetric events have Lineal Energy values y around 1μm. The ordinate is multiplied by y and in the *semi-log* representation the area under the curve delimited by any two values of y is proportional to the fraction of dose delivered by events with lineal energies in this range [7]. The results of the PENELOPE code were obtained using the parameters C_1, C_2, W_{CC}, W_{CR} that would minimize the difference with PITS results especially for the $yf(y)$ spectra (Figure 3). The input parameter C_1 is the average angular deflection

[5] LBNL Report 51487. E. Mainardi, R. J. Donahue, E. A. Blakely. PENELOPE Monte Carlo microdosimetric calculations for 25 keV electrons microbeam in water. *Lawrence Berkeley National Laboratory* **51487**, (September 2003).

produced by multiple elastic scattering along a path length equal to the mean free path between hard elastic events. C_1 is the maximum average fractional energy loss between consecutive hard elastic events. The input parameter W_{CC} is the cutoff energy loss (in eV) for hard inelastic collisions while W_{CR} is the cutoff energy loss (in eV) for hard Bremsstrahlung emission [4]. The results of the two codes appear to be in quite good agreement as regard the shape and y=1μm value at which the peak of $yf(y)$ is evident.
Figure 4 shows the normalized frequency distribution from PITS and from two different PENELOPE simulations, each normalized to PITS results, obtained adopting different set of PENELOPE parameters: PENELOPE ($C_1 = C_2 = 0.2, W_{CC} = W_{CR} = 100$) and PENELOPE with different parameters ($C_1 = C_2 = 0, W_{CC} = 0, W_{CR} = 10$). Changing the values of these parameters it is also possible to change the accuracy and so the speed of the calculations; for this reason a wide variety of cases has been tested and presented in an internal report [6].

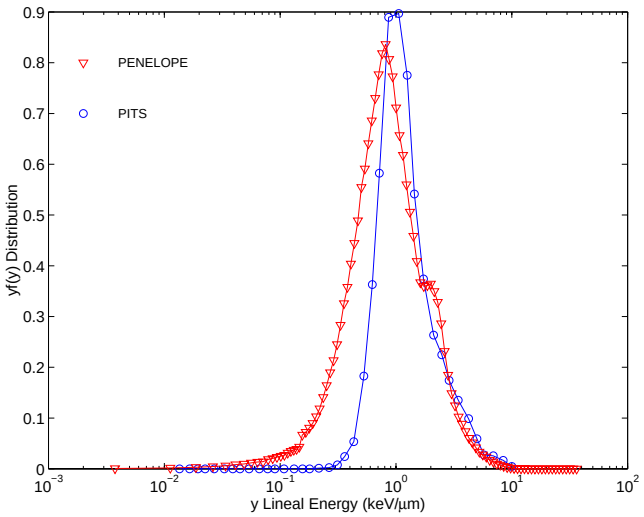

Fig. 3. $yf(y)$ event distribution for first sphere for a 25 keV electron microbeam in water. PITS data presented in [3] Figure 5b for the first sphere at radial distance r=0μm and depth x=0.5μm. PENELOPE data normalized to PITS results.

[6] LBNL Report 53629. E. Mainardi, R. J. Donahue, E. A. Blakely. A user-code for Photons and Electrons Microdosimetry. *Lawrence Berkeley National Laboratory* **53629**.

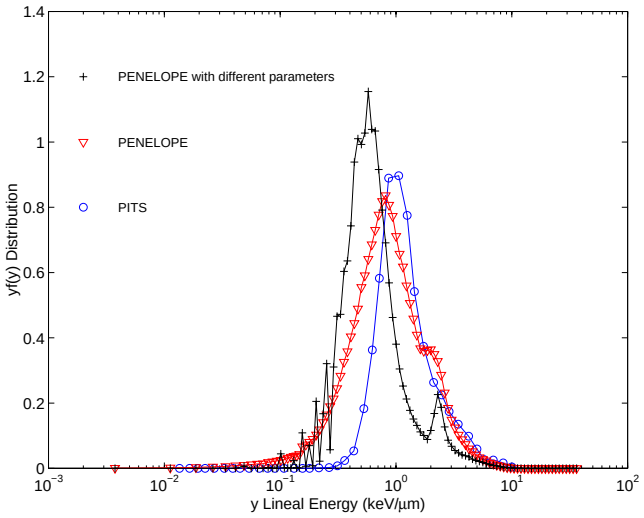

Fig. 4. $yf(y)$ event distribution for first sphere for a 25 keV electron microbeam in water. PITS data presented in [3] Figure 5b for the first sphere at radial distance r=0μm and depth x=0.5μm. PENELOPE data normalized to PITS results for two different simulations: PENELOPE ($C_1 = C_2 = 0.2, W_{CC} = W_{CR} = 100$) and PENELOPE with different parameters ($C_1 = C_2 = 0, W_{CC} = 0, W_{CR} = 10$).

Conclusions

These calculations show the different performances of a user code based on PENELOPE version 2000 and the PITS code for the evaluation of microdosimetric quantities. The results of the PENELOPE code were obtained using the parameters C_1, C_2, W_{CC}, W_{CR} [4] that would minimize the difference with PITS results especially for the $yf(y)$ spectra (Figures 3 and 4). The agreement for lineal energy distribution is evident for the fifth sphere and in most of the spheres with some discrepancies for the first sphere hit by radiation (Figure 2). Also the trends of frequency-mean lineal energy distribution with the two codes seems to be in quite good agreement despite statistical fluctuations of earlier work by PITS (Figure 1).
Further work has been initiated to overcome the disagreement observed in some regions and for certain microdosimetric quantities with the new 2003 version of PENELOPE [5]. One of the new features of the 2003 version is the possibility to improve the reliability of the simulation in materials, such as water, for which there are enough empirical information (private communication with Salvat).
Despite some disagreement this preliminary work demonstrates that PENELOPE can be used for dose and microdosimetric evaluation even with such small sizes and low energies. The results for all the computed microdosimetric quantities in lineal energy, specific energy, energy deposited are presented in an internal report [7] while this work shows only the lineal energy y and spectra as a function of y since for these applications and for discussion of radiation quality in general these answers are more appropriate [6]. Also other works such as [25] have pointed out the possibility of employing the PENELOPE code for microdosimetric applications despite some differences in computational results that are always affected by statistical fluctuations. Microdosimetry is a field where track-structure codes are believed to be superior. If general-purpose Monte Carlo codes with a mixed algorithm like PENELOPE can prove to provide valid answers, using them can draw several advantages here summarized: 1) easier and general availability; 2) possibility to have answers for many materials other than water; 3) more widespread (suggestions and "bug discovery"); 4) more frequent up-grades and benchmark from the authors and from the users and thanks to the interaction of both; 5) generally available code documentation; 6)normally it's more user-friendly, especially if compared with a code created ad hoc for a specific problem.
Further work is planned or under way including:

(1) to study microdosimetric quantities with the new 2003 version of PENE-

[7] LBNL Report 51487. E. Mainardi, R. J. Donahue, E. A. Blakely. PENELOPE Monte Carlo microdosimetric calculations for 25 keV electrons microbeam in water. *Lawrence Berkeley National Laboratory* **51487**, (September 2003).

LOPE;
(2) to adopt the same codes and models to simulate a 12.5 keV photon microbeam;
(3) to benchmark the computations for the 12.5 keV photon against experiments performed at that energy at LBNL's ALS;
(4) to improve the geometrical model of a real single cell and simulate a cluster of cells.

Finally this work has shown that: 1) available general purpose Monte Carlo codes with a simulation scheme like PENELOPE can be used in biological and microdosimetric applications and results are in agreement with those obtained with a track code like PITS if simulation parameters are carefully chosen; 2)there is still a need for experimental results to confirm computational analysis at the microdosimetric level and for low energy photon and electron sources. The microdosimetric quantities computed and analyzed are proportional to RBE values [26,27] and this work is important to study biological effects on living cells; 3)although lot of work as been done in the past [6–9,17] experimental, theoretical and computational work are all needed together for a better understanding of the link between physical description of the nature of radiations and its biological effects.

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Footnotes

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