INTRODUCTION

Tissue-equivalent proportional counters (TEPCs) can be used for characterizing the radiation quality in radiation protection and radiotherapy environments. Usually, they are filled with tissue equivalent gases to simulate tissue site-sizes comparable to the cell size (1 or 2 μm). This affirmation is valid if the energy deposited in the counter is the same as that in the tissue volume. However, TEPCs do not measure the energy deposited in the counter but the ionizations produced microdosimetric sites by the passage of a single ionizing particle. The ionization number is then converted to energy (lineal energy) by a calibration procedure that involves a constant W-value. On the other side, modelled TEPCs using Monte Carlo (MC) techniques give the energy absorbed inside the cavity by single events. In some cases, MC calculations can be complementary to the experimental microdosimetric data, allowing situations to be tested that would otherwise be difficult or impossible to attain. For instance, the simulated TEPC response can be used to evaluate changes in gas composition, due to outgassing effects, gas pressure variations and as a calibration tool.

To this end, theoretical models employed in MC codes need to be validated with experimental data. In this context, the capability of two general-purpose MC codes, FLUKA and PENELOPE, to properly calculate low-LET (60Co and 137Cs gamma radiation) microdosimetric spectra have been investigated and presented in reference (1).

The interest to use multi-purpose codes instead of MC Track Structure Codes is that they hardly can be used to simulate complex geometries due to the large amount of collisions, besides Geant4-DNA code, and provide access to a wide variety of materials, including gases. However, the relatively high electron energy threshold of multi-purpose codes of about 1 keV and the condensed-history MC approach, which group together several collisions in a single step, impose some limitations when recording energy depositions in low density gas materials, where low-energy electrons (below 1 keV) play a dominant role.

A comparison between experimental microdosimetric spectra of 60Co and 137Cs radiation at different simulated sizes (from 0.5 μm to 3.0 μm) in pure propane, versus simulated spectra obtained with two general-purpose codes FLUKA and PENELOPE, which include a detailed simulation of electron-photon transport in arbitrary materials, including gases, is described.

MATERIALS AND METHODS

Measurements were carried out at INFN-LNL laboratory using a spherical sealed TEPC with an internal diameter of 5 cm and a shell of 3 mm thick made of A-150 tissue-equivalent plastic. The counter was filled with pure propane gas at pressures between 5.5 mbar to 32.9 mbar corresponding to site sizes from 0.5 μm to 3.0 μm.

The TEPC was irradiated with 60Co and 137Cs sources of 409 kBq and 1.11 GBq, respectively. More details about the TEPC can be found in reference (2).

The geometry of the simulated TEPC to reproduce the experimental setup is shown in figure 1.

Table 1. Geometry used to modelled a TEPC.

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (mm)</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>50</td>
<td>62</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Rexolite</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

The MC simulated response of a spherical counter filled with pure C3H8 in 60Co and 137Cs photon beams at site sizes from 0.5 μm to 3.0 μm were calculated with FLUKA and PENELOPE codes.

FLUKA 2011.2 version was used in this study. Both energy thresholds for electron transport and for δ-rays production were set to the lowest allowed value of 1 keV in all materials. Frequency distributions of energy depositions at different simulated diameters from 50 μg cm⁻² to 300 μg cm⁻² were calculated by recording the energy deposition using the single scattering mode activated in all materials.

PENELOPE (version 2011) has been used for the present study. In order to perform a detailed simulation, 4 parameters need to be adjusted. C₁ limits the total angular
deflection of (regrouped) soft elastic events. $C_2$ limits the maximum energy loss of regrouped events. These parameters were set to zero to simulate each individual elastic scattering event explicitly. $W_{CC}$ and $W_{CR}$ establish the energy threshold between soft and hard events taking place during both inelastic collision and radiative processes, respectively. $W_{CR}$ was set to zero and $W_{CC}$ was varied from 100 eV to 0.

**RESULTS AND DISCUSSION**

$^{137}$Cs microdosimetric spectra for 1 $\mu$m and 2 $\mu$m calculated with FLUKA and PENELOPE versus experimental data are shown in figure 2.

![Fig. 2. yd(y) distribution as a function of lineal energy for $^{137}$Cs in propane calculated with FLUKA and PENELOPE for 1 $\mu$m and 2 $\mu$m.](image)

For larger site sizes, 3 $\mu$m, an electron of 1 keV gives rise to $\gamma$-values of about 0.5 keV $\mu$m$^{-1}$ while for a 1 $\mu$m an electron of 1 keV gives rise to events of 1.5 keV $\mu$m$^{-1}$. Hence, as the site size decreases, the contribution of electrons below 1 keV in the $\gamma$-spectrum is more important and the transport of these electrons cannot be neglected.

Calculated photon microdosimetric spectra and the experimental data showed overall a good correspondence. However, high differences are found for simulated sites of 1 $\mu$m. Maximum differences of about 10% are found between calculated and experimental data for $\gamma_F$-values, while there is an underestimation of $\gamma_D$-values of about 4% and 8% for FLUKA and PENELOPE respectively, in comparison with experimental data. The agreement between calculated and experimental data is better for FLUKA than PENELOPE, despite the rougher approximations of the first code to model the electron transport. These calculations allow validating the range of applicability of multi-purpose MC codes, in microdosimetry applications. Within the range presented, simulated photon spectra could be employed to supplement microdosimetric spectra for simulated sites larger than 1 $\mu$m.

To improve the TEPC simulated response with PENELOPE, suitable differential cross sections for propane could be implemented instead of using the current model for inelastic collisions.

Further investigation using FLUKA code to calculate microdosimetric spectra in neutron fields and proton beams to compare with experimental data is under progress.

Fig. 3. $yd(y)$ distribution as a function of lineal energy for $^{60}$Co in propane calculated with FLUKA and PENELOPE for 2 $\mu$m

For larger site sizes, 3 $\mu$m, an electron of 1 keV gives rise to $\gamma$-values of about 0.5 keV $\mu$m$^{-1}$ while for a 1 $\mu$m an electron of 1 keV gives rise to events of 1.5 keV $\mu$m$^{-1}$. Hence, as the site size decreases, the contribution of electrons below 1 keV in the $\gamma$-spectrum is more important and the transport of these electrons cannot be neglected.

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