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Simulated response of a multi-element thick gas electron multiplier-based microdosimeter to high energy neutrons

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HIGHLIGHTS

- A multi-element thick gas electron multiplier (THGEM)-based microdosimeter is studied for high energy neutrons.
- Quality factors are obtained for neutrons by simulating 1 μm of tissue.
- An energy-independent dose-equivalent response is achieved between 14 MeV and 5 GeV.

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ABSTRACT

The response of a microdosimeter for neutrons above 14 MeV is investigated. The mean quality factors and dose-equivalents are determined using lineal energy distributions calculated by Monte Carlo simulations (Geant4 toolkit). From 14 MeV to 5 GeV, the mean quality factors were found to vary between 6.00 and 9.30 and the dose-equivalents were in agreement with the true ambient dose-equivalent at the depth of 10 mm inside the ICRU sphere, $H^*(10)$. An energy-independent dose-equivalent response around a median value of 0.86 within 22% uncertainty was obtained. Therefore, the microdosimeter is appropriate for dose-equivalent measurement of high-energy neutrons.

1. Introduction

Neutrons produce secondary charged particles when they interact with matter. In addition, neutron fields are usually mixed with gamma rays. Such characteristics cause challenges in neutron dosimetry (Attix, 2008). Studies showed that tissue equivalent proportional counters (TEPCs) are appropriate devices for neutron dosimetry (ICRU, 1983). TEPCs were first introduced in 1955 (Rossi and Rosenzweig, 1955), made of a tissue-equivalent (TE) plastic wall filled with a TE gas. By decreasing the TE gas pressure, a TEPC can simulate micron-sized tissue volumes. It measures the microdosimetric quantity of "lineal energy", defined as the ratio of energy imparted to the gas to the mean chord length $\bar{l}$ of the simulated tissue volume (for a convex tissue body with volume V and surface S, $\bar{l} = 4V/S$) (ICRU, 1983). Since the lineal energy is directly related to the dose-equivalent (Gerdung et al., 1995; Waker, 1995), a TEPC can determine the dose-equivalent of neutrons better than other neutron dosimeters.

When coupled to a fast pulse processing system, a standard 0.5 in TEPC can be reliably operated at a neutron dose rate of 20 mGy min^{-1} (Spirou et al., 2008). At higher dose rates this TEPC suffers from pulse pile up. To overcome this problem, the size of the TEPC should be reduced, which leads to difficulty in fabrication and in the construction of a tiny anode wire. To overcome the difficulties, gas electron multipliers, (GEMs) (Sauli, 1997), micro-pattern gaseous detectors (Sauli and Sharma, 1999) and thick gas electron multipliers (THGEMs) (Chechik et al., 2004) were developed. TEPCs based on these multipliers were investigated for use in neutron microdosimetry (Anjomani et al., 2014; Byun et al., 2009; Farahmand et al., 2004; Hanu et al., 2010; Moslehi et al., 2016; Orchard et al., 2011; Wang et al., 2007). Recently, a multi-element THGEM-based microdosimeter was designed (Moslehi and Raisali, 2017), which presents a flat dose-equivalent neutron response from thermal to 14 MeV energy simulating a 1 μm of tissue. It was designed as a cylinder that includes 7 main Polymethyl Meta Acrylate (PMMA) layers. Each layer contained a cathode, 37 cavity elements, a THGEM, an induction gap and an anode. The completed design had a diameter of 68 mm and a height of 76 mm, including 259 identical cavities (a 7 × 37 array) to increase the sensitivity to neutrons (Rossi, 1983). The thickness of PMMA walls surrounding the cavities was 10 mm, similar to the depth of 10 mm inside the ICRU sphere to determine the ambient dose-equivalent, H*(10).

Given fact that many available neutron sources, like ^{252}Cf, ^{241}Am-Be, reactors and accelerator-based reactions emit neutrons of energy

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less than 14 MeV, most of the interest in neutron dosimetry focused on this energy range. However, there are some cases where neutrons of greater energy exist, for example in the vicinity of high energy accelerators (Agosteo et al., 2008), fast neutron therapy facilities (Wambersie et al., 1984) and in space (Barth et al., 2003). Dosimetry of these high-energy neutrons is needed, but few are reported in the literature. Since the fields of such neutrons are complicated, mixed and even unknown, one has to use microdosimetry in these fields. The dose for neutrons produced by (p,n) interaction were measured using a TEPC (Kliauga et al., 1990; Menzel et al., 1990; Pihet et al., 1984). Ambient dose and ambient dose-equivalent conversion factors were determined for high energy neutrons up to 5 GeV (Pelliccioni, 2000; Sannikov and Savitskaya, 1993). The microdosimetric calculations of the dose-equivalent response for neutrons above 20 MeV was performed simulating a spherical TEPC (Alexeev et al., 1998). Change in the dose and lineal energy spectra due to different shieldings used in the Los Alamos high energy neutron fields in the energy region of 2–200 MeV was investigated (Badhwar et al., 2000). Lineal energy distribution for the neutrons ranging from 8 keV to 65 MeV was measured by a spherical TEPC of 12.5 cm in diameter simulating 3 μm of tissue (Nunomiya et al., 2002). In addition, lineal energy distribution at the CERN high energy facility was measured and simulated (Rollet et al., 2007). The response of some neutron detectors including a HANDI-TEPC (Homburg Area Dosimeter) was measured at the high energy mixed radiation fields in the vicinity of CERN's high energy accelerator (Mayer et al., 2007).

In this paper, the response of the microdosimeter of Moslehi and Raisali (2017) is determined for the energies from 14 MeV up to 5 GeV. The mean quality factors and dose-equivalents were determined using the lineal energy distributions calculated by the Geant4 simulation toolkit (Agostinelli et al., 2003). It is an open-source toolkit that includes various physics models for electromagnetic and hadronic interactions, appropriate for microdosimetry calculations. The dose-equivalents were compared with the reported true ambient dose-equivalent values.

2. Methods

The geometry and composing materials of the microdosimeter of Moslehi and Raisali (2017) were defined using Geant4 toolkit. Twenty five different energies from 14 MeV to 5 GeV were considered, for which H*(10) values were reported in the literature (Leuthold et al., 1992; Pelliccioni, 2000). From 14 MeV to 20 MeV, the QGSP_BERT_HP physics model was used to transport neutrons and their secondary charged particles, suited for simulations in the energy range less than 20 MeV (Taylor et al., 2015). For higher energies, the QGSP_BERT model was used instead. Also, a length (range) cut-off equal to 1 mm was selected for the both physics models. Utilizing this cut-off value, Geant4 produced secondary particles with ranges greater than or equal to 1 mm. The source emitted mono-directional neutrons from a thin circular surface at a distance of 0.5 m impinging normally on the top wall of the microdosimeter. It was similar to the real situation when neutrons are emitted from a point source. Assuming the size of the microdosimeter and its 0.5 m distance from the source, the neutrons hitting the microdosimeter are emitted in a very small solid angle and the difference between the shortest and the longest distances they travel is about 1 mm. Therefore, one can suppose that they are almost mono-directional. It only reduces the computation time and has no impact on the results. The space between the microdosimeter and the source was assumed to be filled with the air at atmospheric pressure.

To obtain the lineal energy distributions, energy imparted to the TE gas in each ionization event was calculated and divided by the mean chord length of a tissue volume of $d = 1$ μm in diameter (ICRU, 1983). An algorithm was written to provide 350 logarithmic bins of lineal energy between 10^{-3} keV μm^{-1} and 10^{4} keV μm^{-1} (assuming 50 bins per decade) and to place any lineal energy (event) in its corresponding bin. After transporting all neutrons of a given energy, the number of events in each bin, N, was determined. Then, the frequency distribution, $f(y)$ and dose distribution, $d(y)$ of lineal energy were calculated. Next, the normalized variations of $yd(y)$ vs. y (ICRU, 1983) was plotted as the standard representation of lineal energy distribution. For each energy, the number of incident neutrons was set so that it was large enough (minimum 10^7 neutrons) to achieve a relative statistical error smaller than 1% for the total energy deposition value in the TE gas.

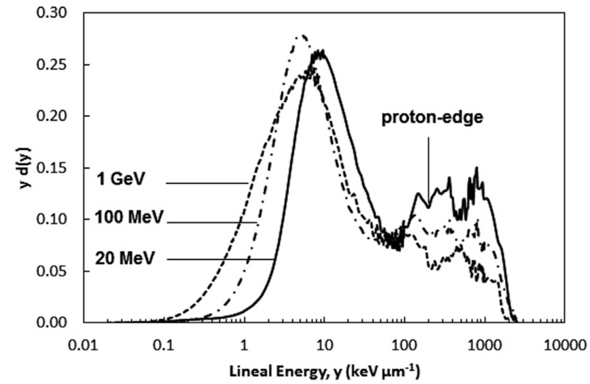

Fig. 1. Normalized lineal energy distributions for 20 MeV, 100 MeV and 1 GeV neutrons.

3. Results and discussion

Fig. 1 shows the lineal energy distribution for 20 MeV, 100 MeV and 1 GeV neutron energies. It shows the typical peaks corresponding to the recoil protons (the larger one) and heavy ions (Carbon, Oxygen and alpha particles produced in (n,α) interactions) (the small one). The maximum lineal energy of the proton peak, when simulating a 1 μm of tissue is 145 keV μm^{-1} (corresponding to the proton-edge). The maximum possible lineal energy produced by a proton with a track that coincides the largest chord, therefore, independent of neutron energy.

According to Fig. 1, as the neutron energy increases, the proton peak tends to a smaller lineal energy, due to the decrease of the stopping power of secondary charged particles and the decreasing the imparted energy to the TE gas (Moslehi et al., 2016). Increasing the neutrons energy from 14 M to 20 MeV, the heavy ion peak becomes stronger ($yd(y)$ values grow), because the cross-sections of elastic scattering from heavy ions like carbon and oxygen and also (n,α) interactions increases (Chadwick et al., 2006). However, as the neutron energy reaches the GeV region range, the heavy ion-peak becomes weaker ($yd(y)$ values decrease), due to the decrease in the interaction cross-section.

Fig. 2 shows the variation of frequency-mean lineal energy, $\bar{y}_F$ and dose-mean lineal energy, $\bar{y}_D$ (ICRU, 1983) vs. neutron energy. These

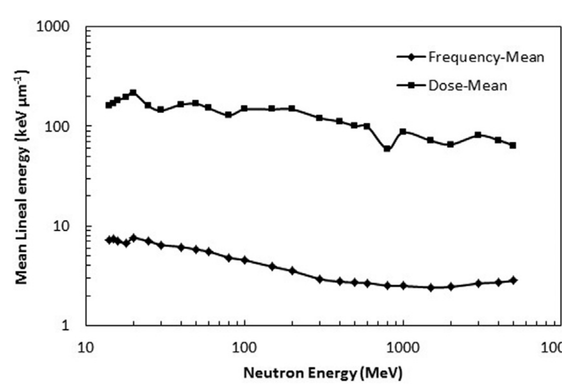

Fig. 2. Frequency-mean and dose-mean lineal energies for different neutron energies.

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