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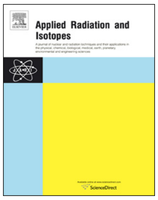

Modelling the absorbed dose rate of the beta standard BSS2 ^{147}Pm source

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ABSTRACT

The dosimetric measurements of ^{147}Pm beta radiation beams have limitations due to their low energy, low dose rate, great dispersion and attenuation in air or tissue. In this work, the Monte Carlo model was developed for a ^{147}Pm absorbed dose rate determination. This model consists of an extrapolation chamber and a ^{147}Pm beta radiation source. Moreover, the absorbed dose rate was determined by experimental measurements and the MCNP Monte Carlo code was used. The relative number of particles that crossed the radioactive source window and the particles that crossed the extrapolation chamber entrance window were determined. The source fluence spectrum was also determined. The results of the simulation and the experimental calculations are in agreement with the absorbed dose rate from the PTB calibration certificate. The results obtained are considered acceptable, and they agree within the uncertainties. The difference between the experimental result and that from the Monte Carlo model, compared to that from the calibration certificate, was only 0.8% in both cases.

1. Introduction

Beta radiation doses caused by an open source may be 50 times higher than doses produced by gamma rays with the same activity. The risk due to beta radiation appears mainly in the case of exposure to contaminated materials and handling at small distances or contact of beta-emitting radioactive products (ICRU, 1997).

The main difficulty of beta dosimetry is due to its short range in matter (ICRU, 1997). The dose varies rapidly depending on the distance between the source, the measurement point and the tissue depth. Within the tissue this phenomenon increases due to the strong attenuation of beta radiation. These problems are complicated by the large dispersion of beta radiation in the air (ICRU, 1997).

Low-energy beta emitters, such as ^{147}Pm, principally irradiate the epidermis. When the doses are very high, they can cause necrosis of the epidermis, that is, the pathological death of the cells in the middle epidermis. The ^{147}Pm can represent a beta radiation hazard in research where it is used as a standard (ICRU, 1997).

The quantity established for beta radiation measurements is the absorbed dose rate. The primary standard instrument for measuring this quantity is the extrapolation chamber (Böhm, 1886; NIST, 2010; Caldas, 1980; Bakshi et al., 2013; Vahabi et al., 2014). This type of ionization chamber is based on the Bragg-Gray theory, and it is capable to vary its volume by changing the separation of its electrodes (ISO, 2004).

The Monte Carlo radiation transport methods are widely used in radiation dosimetry and detectors design. The simulations allow the calculation of physical parameters, as well as the design of complex geometries similar to the actual physical problem. In some studies, the absorbed dose rate of beta radiation has been determined and subsequently compared with experimental measurements (Behrens, 2013; Vahabi et al., 2014; Selvam et al., 2005; Faria et al., 2015; Polo et al., 2017).

The objective of this work is to develop a Monte Carlo model for a ^{147}Pm source and an extrapolation chamber for an absorbed dose rate determination. Experimental measurements were carried out. The results of this work are of great importance for the Laboratory for Calibration of Instruments (LCI) at the IPEN/CNEN/Sâo Paulo, Brazil. They will be used in the establishment of a primary standard for beta radiation and for the determination of some correction factors.

2. Materials and methods

2.1. Extrapolation chamber PTW model 23392 and ^{147}Pm source

For the simulation and measurements, the PTW type 23392 extrapolation chamber of LCI/IPEN was used. Fig. 1 shows a cross section view of the extrapolation chamber basic components (Fig. 1).

The charge measurements were taken using a Keithley model 6517B high-impedance electrometer.

The utilized ^{147}Pm source is part of the LCI/ IPEN beta secondary standard BSS2. The main features of this source are: nominal activity of

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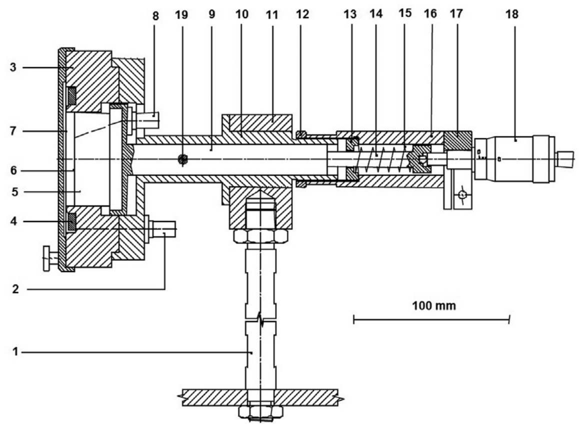

Fig. 1. Cross section of the Böhm extrapolation chamber type 23392. 1: stand, 2: polarizing voltage socket, 3: acrylic housing, 4: tension ring, 5: PMMA block, 6: graphite coated surface, divided into collecting electrode and guard ring, 7: entrance foil, 8: collecting electrode socket, 9: sliding-fit rod, 10: central guide for rod, 11: holder, 12: nut, 13: threaded ring, 14: bolt, 15: spring, 16: tube, 17: clamp, 18: micrometer screw, 19: piston locking screw, 20: protective cover (PTW, 2002).

3.7 GBq; mean beta energy of 0.06 MeV and calibration distance of 20 cm. This source requires the use of a special Hostaphan filter in the radiation beam at the BSS2 system. The calibration date of this source is 19/11/2004 (PTB, 2005)

2.2. Determination of the experimental absorbed dose rate

To determine the absorbed dose rate in the tissue with an extrapolation chamber, the expression from (ISO, 2004) is used:

$$\dot{D}_\beta = \frac{(\overline{W}_o/e)s_{t,a}}{\rho_{a0}*a}\left[\frac{d}{dl}\{kk`I(l)\}\right]l = 0 \tag{1}$$

where $(\boldsymbol{\overline{W}_o/e})$ is the quotient of the mean energy to produce an ion pair in air under reference conditions and the elementary charge; $\boldsymbol{s_{t,a} = 1.\ 124}$ is the quotient of mass-electronic stopping powers of ICRU tissue and air for ^{147}Pm; $\boldsymbol{\rho_{a0}}$=1. 1974 kg/m^3 is the density of air at reference conditions which are defined for the parameters: ambient temperatureT_0 = 293.15 K, atmospheric pressure p_0 = 101.325 kPa and relative humidity r_0 = 0.65; a is the effective area of the extrapolation chamber collecting electrode; *I(l)* is the ionization current; k is the product of the correction factors (ISO, 2004) which are dependent on the chamber depth or some other varying parameters, consisting of the following correction factors: k_{ac} for attenuation of beta-particles in the collecting volume, k_{ad} for air density in the collecting volume, k_{abs} for attenuation and scattering of beta-particles between the source and the collecting volume, k_{de} for radioactive decay, k_{di} for axial non-uniformity, k_{pe} for perturbation of the beta-particle flux density by the side walls of the extrapolation chamber, k_{sat} for ionization collection losses due to ion recombination; k` is the product of correction factors (ISO, 2004) which are independent of the chamber depth or are constant during the measurement. They consist of the following correction factors: k_{ba} for backscattering from the collecting electrode and guard ring, k_{br} for Bremsstrahlung from the beta-particle source, k_{el} for electrostatic attraction of the entrance window, k_{hu} for variations of $\boldsymbol{\overline{W}_o}$ due to variations of the relative air humidity, k_{in} for interface effects, k_{ra} for radial non-uniformity; $\left[\frac{d}{dl}\{\boldsymbol{kk`I(l)}\}\right]\boldsymbol{l = 0}$ is the limiting slope value for $l = 0$ of the corrected ionization current versus chamber depth.

The correction factors k and k` were determined according to Böhm (1886) and ISO 6980–2:2004 report (ISO, 2004).

The absorbed dose rate for the ^{147}Pm source was determined experimentally for a distance of 20 cm according to its calibration certificate (PTB, 2005). The applied voltage and the chamber depth were varied from ± 5 V to ± 25 V and from 0.5 mm to 2.5 mm, respectively. For the determination of the ionization current, six measurements of electric charge were taken for each case with a fixed integration time of 120 s.

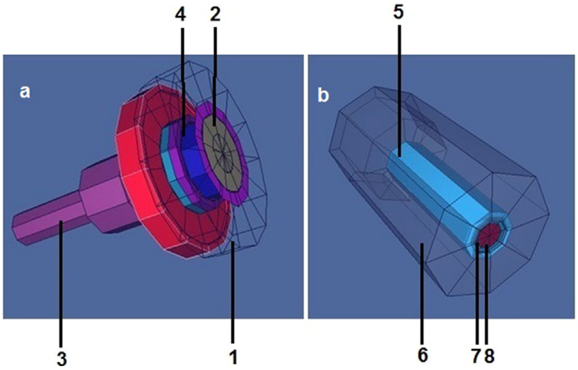

Fig. 2. MCNP5 model of the extrapolation chamber (a) and the ^{147}Pm radiation source (b). 1: acrylic housing, 2: entrance foil, 3: holder, 4: PMMA block, 5: aluminum, 6: steel, 7: titanium, 8: Pm_2O_3.

2.3. MCNP5 model of the extrapolation chamber and the ^{147}Pm radiation source

MCNP5 is a Los Alamos 3-D Monte Carlo radiation transport code capable of tracking neutrons, photons and electrons and applied for the coupled transport of neutrons / photons / electrons radiation. The MCNP code includes general sources, criticality and surface sources and flexible tally structure. In addition, it has a collection of variance reduction techniques and a wide collection of cross-section data (MCNP, 2008).

For the simulation, the Monte Carlo model already reported for the extrapolation chamber was utilized (Polo et al., 2017). The material densities used in the simulation for aluminum, steel, titanium, and Pm_2O_3 were 2.85, 8.06, 4.4 and 6.85 g/cm^3, respectively (ICRU, 1997). Fig. 2 shows the MCNP5 model of the extrapolation chamber and the ^{147}Pm radiation source (Vised version X_22 S).

In the simulation, the chamber null depth was considered as (0.102 ± 0.021) mm. The actual dimensions of the source were considered including its active part and its shielding. The source energy spectrum used was taken based on the ICRU Report No.56 (ICRU, 1997).

The procedure for the absorbed dose rate determination was the same of an earlier study (Polo et al., 2017). The tally *F8 (energy deposition) was also used. The absorbed dose rate per gram was calculated according to MIT (MIT, 2017) by the following expression:

$$\dot{D} = A*\overline{E}*(\frac{\text{MeV}}{\text{g. s}})\quad *1,\ 60*10^{-13}*(\frac{\text{J}}{\text{MeV}})*10^3\ \left(\frac{\text{g}}{\text{kg}}\right) = 1,\ 60*10^{-10}*A*\overline{E}\quad \left(\frac{\text{Gy}}{\text{s}}\right) \tag{2}$$

where A is the specific source activity in Bq/g and $\overline{E}$ is the mean energy in MeV per disintegration.

According to ISO (2004), the absorbed dose rate in the tissue ($\dot{D}_t$) in the sensitive volume of the extrapolation chamber was calculated by the expression:

$$\dot{D}_t = \dot{D}\quad *s_{t,a} \tag{3}$$

where $s_{t,a}$ is the quotient of mass-electronic stopping powers of ICRU tissue and air.

Tally F1 was used for determination of the relative number of particles that crossed the radioactive source window and the particles that crossed the extrapolation chamber entrance window. The source fluence spectrum was determined using tally F4.

Table 1
Correction factors for the absorbed dose rate determination using the extrapolation chamber and the BSS2 ^{147}Pm source.

Factor	Value	
k_{de}	24.04 ± 0.17	
k_{abs}	1.0002 ± 0.0080	
k_{ba}	1.010 ± 0.003	
k_{br}	0.9900 ± 0.0020	
k_{hu}	1.0000 ± 0.0010	
k_{in}	1.0000 ± 0.0010	
k_{ra}	1.000 ± 0.005	
k_{el}	1.0000 ± 0.0010	
	Chamber depth	
	0.5 mm	**2.5 mm**
k_{sat}	1.0024 ± 0.0020	1.0106 ± 0.0020
k_{ac}	1.007 ± 0.010	1.033 ± 0.010
k_{di}	1.0025 ± 0.0010	1.0125 ± 0.0010
k_{pe}	1.0010 ± 0.0020	1.0049 ± 0.0020
k_{ad}	1.076 ± 0.006	1.078 ± 0.006

3. Results and discussion

The correction factors k, k ', and their respective uncertainties are shown in Table 1. In the case of the factors that depend on the extrapolation chamber depth, the values corresponding to the depths of 0.5 mm and 2.5 mm are shown. The uncertainties were evaluated according to the ISO 6980–2:2004 report (ISO, 2004).

The correction factors are in agreement with the values reported by Böhm (1986) and ISO (2004). The coefficient for radioactive decay is k_{de} = (24.04 ± 0.17), taking into account the source calibration date (PTB, 2005).

It was necessary to determine the chamber real null depth, taking measurements of the ionization current for each chamber depth. The measured currents were corrected for the reference conditions of temperature and pressure. According to ISO (2004), current measurements at both positive and negative polarities were taken. Fig. 3 shows the graph for the extrapolation chamber null depth determination.

The chamber real null depth was also determined for ^{90}Sr/^{90}Y and ^{85}Kr BSS2 sources following the same methodology as for the ^{147}Pm source. The values obtained were (0.0938 ± 0.0014) mm and (0.096 ± 0.009) mm for the ^{90}Sr/^{90}Y and ^{85}Kr sources respectively. All values are within the range of uncertainties for the three sources.

For the extrapolation curve determination, the chamber depths were corrected taking into account the null depth. The limiting slope ($\left[\frac{d}{dl}\{kk'I(l)\}\right]l = 0$) was determined by a least-squares fitting of the extrapolation curve to a polynomial function. The linear correlation coefficient of the linearly adjusted curve was 0.9917 and the limiting slope was (0.299 ± 0.005) pA/m. By means of Expression (1) the absorbed dose rate in the tissue at null depth (on the surface of the extrapolation chamber entrance window) was determined as (12.9 ± 0.5) μGy/s.

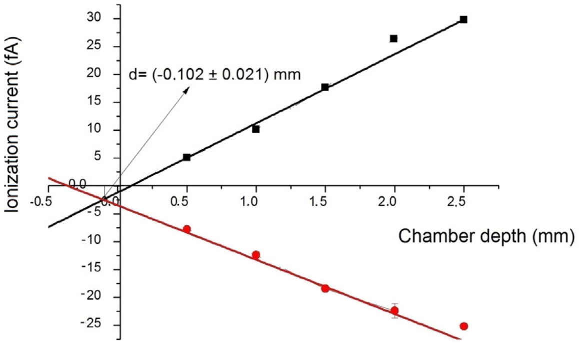

Fig. 3. Extrapolation chamber null depth (d) determination. (Maximum uncertainty: 5.9%).

Table 2
Absorbed dose rate determination.

Method	Absorbed dose rate (μGy/s)	*Δ (%)
Experimental measures	(12.9 ± 0.5)	0.8
Monte Carlo method	(12.7 ± 1.8)	0.8
Calibration certificate	(12.8 ± 0.3)	–

* Δ: difference in relation to the calibration certificate.

The radiation transport was simulated following individual electron and photon histories that went through the whole geometry, and the ITS mode for the electron transport was used (MCNP, 2008). A detailed electron physics treatment, including Compton recoil, photo-electric effect, photon Auger and knock-on electron creation, has been considered.

The number of initial particles (nps) for the simulation was 100×10^{8}. The ten MCNP code statistical tests were fulfilled (MCNP, 2008). The energy deposited (tally *F8) was (4.21×10^{-8}) MeV, and the relative statistical error was only 0.06. By means of Expressions (2) and (3), the absorbed dose rate in tissue was determined by Monte Carlo method, and its value was (12.7 ± 1.8) μGy/s.

Table 2 shows a comparison between the experimental values of the absorbed dose rate, the dose rate determined by the Monte Carlo method and the dose rate from the calibration certificate.

The uncertainties concerning the calculation of the absorbed dose rates were determined taking into account the measurements taken with the extrapolation chamber, the electrometer and the propagation of the uncertainties of the different parameters. Uncertainties of type A and type B were considered and the factor $k = 2$, for a coverage probability of approximately 95%.

The relative number of particles that crossed the source window was $(951.03 \pm 0.10) \times 10^{-4}$ and the relative number of particles that crossed the extrapolation chamber entrance window was $(48.3 \pm 0.6) \times 10^{-7}$. These parameters indicate the strong absorption of electrons in the air and in the beam-flattening filter, which is a characteristic of the ^{147}Pm source.

Fig. 4 shows the resulting spectral particle fluence obtained in the simulation.

The resulting spectral particle fluence of the Fig. 4 is in agreement with the graphs presented by Böhm (1986). The shape of the spectrum coincides with the graphs of ICRU Report 56 (1997).

The results of the simulation and the experimental calculations are in agreement with the absorbed dose rate from the PTB calibration certificate. The results obtained are considered acceptable, considering that they are within the uncertainty range. The difference between the experimental and the Monte Carlo model results, compared to that from the calibration certificate, was only 0.8% in both cases.

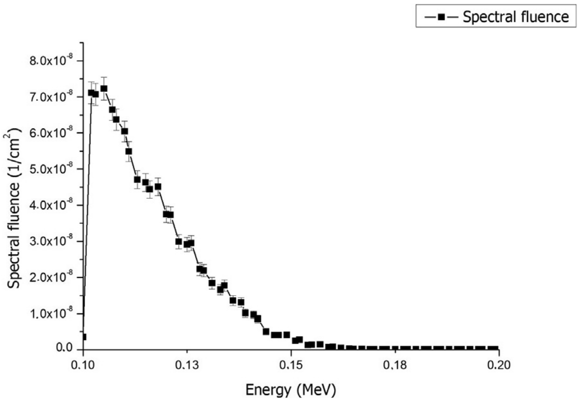

Fig. 4. Spectral particle fluence of ^{147}Pm source.

4. Conclusions

In this work, a Monte Carlo model was developed for the extrapolation chamber and the ^{147}Pm BSS2 source of the LCI/IPEN.

The results of the simulation and the experimental calculations are in agreement with the absorbed dose rate from the PTB calibration certificate.

The agreement of the results of the simulation and the experimental calculations with the absorbed dose rate from the PTB calibration certificate shows that the Monte Carlo model is suitable for the establishment of a primary standard for beta radiation and for the determination of some correction factors.

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