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Determination of correction factors in beta radiation beams using Monte Carlo method

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ABSTRACT

The absorbed dose rate is the main characterization quantity for beta radiation. The extrapolation chamber is considered the primary standard instrument. To determine absorbed dose rates in beta radiation beams, it is necessary to establish several correction factors. In this work, the correction factors for the backscatter due to the collecting electrode and to the guard ring, and the correction factor for Bremsstrahlung in beta secondary standard radiation beams are presented. For this purpose, the Monte Carlo method was applied. The results obtained are considered acceptable, and they agree within the uncertainties. The differences between the backscatter factors determined by the Monte Carlo method and those of the ISO standard were 0.6%, 0.9% and 2.04% for ^{90}Sr/^{90}Y, ^{85}Kr and ^{147}Pm sources respectively. The differences between the Bremsstrahlung factors determined by the Monte Carlo method and those of the ISO were 0.25%, 0.6% and 1% for ^{90}Sr/^{90}Y, ^{85}Kr and ^{147}Pm sources respectively.

1. Introduction

In beta radiation beams, for a correct measurement of the absorbed dose rate at a point in a phantom, a very small detector is needed. That detector shall have absorption and backscattering characteristics similar to those of the medium of which the phantom is composed of (ISO, 2004). To ensure these conditions, some correction factors have to be determined.

In measurements with an extrapolation chamber in beta radiation fields, some of the incident particles are backscattered in the chamber sensitive volume by the collecting electrode and also by the guard ring (Böhm, 1986; ISO, 2004). As the collecting electrode and the guard ring are made of a different material than tissue, a factor must be introduced to correct this difference. In addition to this, a part of the interactions is caused by Bremsstrahlung emitted by the radioactive source. Although this radiation can usually be neglected, its contribution may be important if the calibration is relative to the absorbed dose rate in tissue at the reference depth of 0.07 mm (Böhm, 1986; ISO, 2004). Therefore, it is necessary to determine the correction factors due to the variation in backscattering in one medium relative to the reference one, and due to Bremsstrahlung.

Measurements of the backscattering factor relative to air and other media have been taken for several beta-emitting radionuclides (Snymang and Claytos, 1963; Owen, 1973; Murthy and Böhm, 1982; Böhm, 1986; Nunes et al., 1993; Hansen et al., 2018). Likewise, experimental measurements have been taken to determine the Bremsstrahlung factor in several works (Schüren and Heinzelman, 1980; Caldas, 1980; Böhm, 1986; Antonio, 2013).

The Monte Carlo method constitutes a fundamental tool for the determination and evaluation of absorbed dose and other quantities in applications of medical physics. Due to the increased use of this method, several computer codes have been developed for specific use and for general applications. Among those codes are MCNP, EGSnrc, BEAMnrc, PENELOPE, ITS, ETRAN and GEANT (Yoriyaz, 2009).

The Monte Carlo codes have also been used for the simulation of radiation detectors. Specifically, some extrapolation chambers and beta sources have been simulated for the determination of some physical parameters and the transmission factors, and the absorbed dose rates have been calculated (Nunes and Prestwich, 1993; Cho and D Reece, 1999; Palani Selvam et al., 2005, 2016; Neves et al., 2012; Behrens, 2013; Vahabi et al., 2014; Faria et al., 2015; Chang et al., 2017; Polo et al., 2017; Hansen et al., 2018).

The objective of this work was the determination of correction factors for the backscatter of the collecting electrode and guard ring, and the correction factor for Bremsstrahlung in the Beta Secondary Standard type 2 (BSS2) beta radiation beams. The results were

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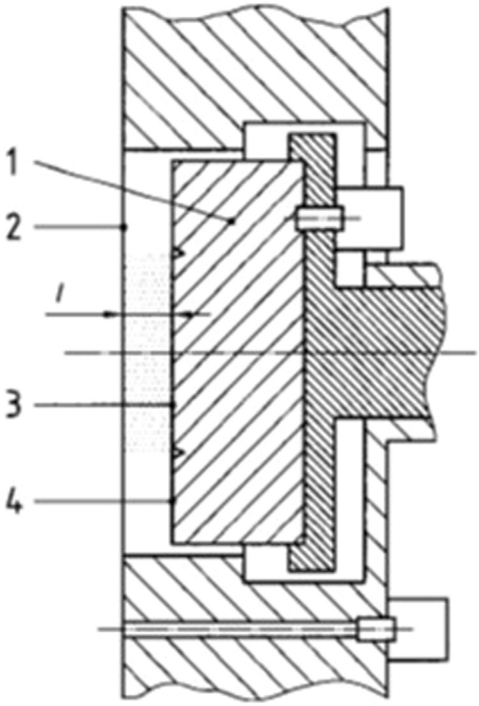

Fig. 1. Cross section of an extrapolation chamber. Main components: 1 - piston, 2 - entrance window, 3 - collecting electrode, 4 - guard ring, l - chamber depth (ISO, 2004).

compared with the correction factors determined by means of experimental methods (ISO, 2004). In addition, the associated uncertainties of the factors were calculated. The results of this work are of great importance for the Laboratory for Calibration of Instruments (LCI/IPEN) in the establishment of the primary standard radiation beams.

2. Materials and methods

2.1. PTW Extrapolation chamber and beta radiation sources

To determine the correction factors, the PTW type 23392 extrapolation chamber of the LCI/IPEN was simulated. Fig. 1 shows the cross section of an extrapolation chamber and its main components. The radioactive sources of the BSS2 system were also simulated. The source characteristics are shown in Table 1 (BSS2, 2005; PTB, 2005a, 2005b, 2005c).

For the simulation, the calibration distance of 11 cm (without filter) was used in the case of the ^{90}Sr/^{90}Y source. In the case of ^{85}Kr and ^{147}Pm sources, the Hostaphan (Polyethylene Terephthalate (PET)) beam flattening filters were simulated.

2.2. MCNP5 model of the extrapolation chamber and the radiation sources

The radiation transport code used for the simulations was MCNP (2008). It can be applied for neutron, photon, electron, or coupled neutron/photon/electron transport. Some areas of application of this code are: radiation protection and dosimetry, medical physics, radiation shielding, radiography, nuclear criticality safety, detector design and analysis, accelerator target design, fission and fusion reactor design, decontamination.

Table 1
Characteristics of the BSS2 beta sources.

Characteristic	Radionuclide		
	^{147}Pm	^{85}Kr	^{90}Sr/^{90}Y
Nominal activity	3.7 GBq	3.7 GBq	460 MBq
Mean beta energy (MeV)	0.06	0.24	0.8
Calibration distance (cm)	20	30	11, 20, 30, 50
Calibration date	19/11/2004	30/11/2004	19/11/2004
Approximate half-life (days)	958	3915	10,483

For the simulations, the MCNP5 Monte Carlo model previously reported for the extrapolation chamber was used (Polo et al., 2017). The extrapolation chamber null depth was considered in the simulation: (0.102 ± 0.021) mm. For the definition of the geometry of the radioactive sources, their active parts and their shielding were also considered.

2.3. Determination of the backscatter and Bremsstrahlung correction factors

For the determination of the backscatter factor (k_{ba}) by the Monte Carlo method, an extrapolation chamber was simulated without considering the components in backscatter free conditions and another chamber with all the components (Fig. 2). The procedure was undertaken for all three sources. The backscatter factor of Polymethyl Methacrylate (PMMA) relative to air can be obtained by Eq. (1):

$$B_{PMMA} = E/E_{ar} \tag{1}$$

where E is the deposited energy by the radiation considering all the components and E_{ar} is the deposited energy of the chamber without considering the components.

According to Böhm (1986), the backscatter factor of the tissue can be determined by Eq. (2):

$$B_t = 1+(B_{PMMA}-1)^* \quad \overline{Z_t}/\overline{Z_{PMMA}} \tag{2}$$

where $\overline{Z_t}$= 6,50 and $\overline{Z_{PMMA}}$ = 5,85 are the atomic numbers of the tissue and the PMMA respectively. The correction factor k_{ba} can be determined by Eq. (3):

$$k_{ba} = B_t/B_{PMMA} \tag{3}$$

For the determination of the Bremsstrahlung correction factor, according to Böhm (1986), low atomic number absorbers must be placed in front of the extrapolation chamber entrance window. These absorbers have to be sufficiently thick to block beta radiation, but to allow Bremsstrahlung to pass through (Böhm, 1986). For the factor determination by the Monte Carlo method, the following absorber conditions were simulated: for the ^{90}Sr/^{90}Y source, a PMMA absorber of 10 mm thickness and, for the ^{85}Kr and ^{147}Pm sources, Hostaphan absorbers of 3 mm, 4 mm and 0.25 mm thick, respectively. These absorber thicknesses and materials were recommended by Böhm (1986).

The Bremsstrahlung correction factor was determined by Eq. (4):

$$k_{br} = E - E_{br}/E \tag{4}$$

where E is the energy deposited in the cavity of the extrapolation chamber without the use of absorbers and E_{br} is the energy deposited in the cavity with the use of absorbers.

3. Results and discussion

The initial number of particles for the simulation of each source was 10^8, and the Integrated TIGER Series electron physics (ITS) mode for electron transport was used. In all cases, the statistical tests carried out by the MCNP were fulfilled (MCNP, 2008).

Table 2 shows a comparison between the interactions in the cavity of the extrapolation chamber (sensitive volume) without considering the components and the chamber with all the components, for each radiation source.

Table 3 shows the energy deposited by the radiation in the extrapolation chamber without considering the components and in the chamber with all the components, for each radiation source.

In the case of electrons, Table 2 (columns “b”) shows an increase in

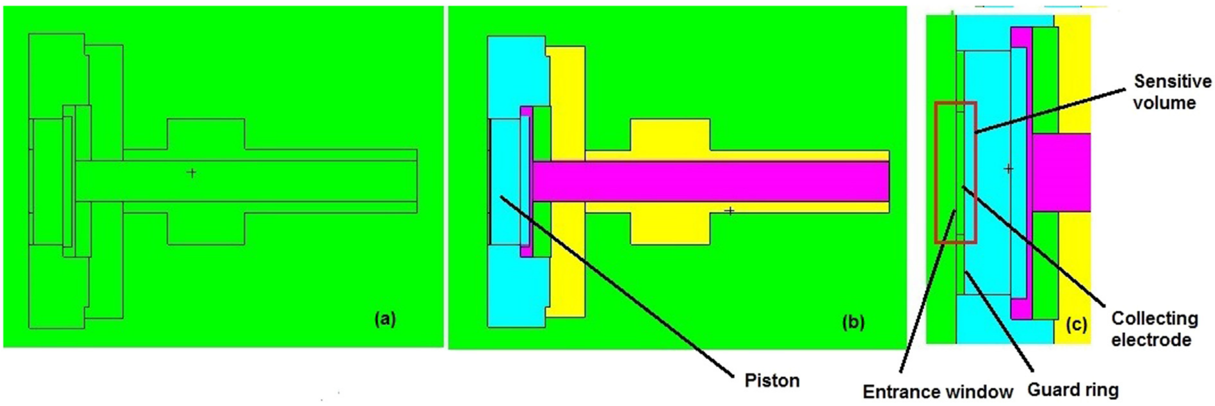

Fig. 2. MCNP5 model of the extrapolation chamber: a) chamber without components; b) with all components; c) main components of the extrapolation chamber.

Table 2
Interactions in the cavity of the extrapolation chamber (sensitive volume) without considering the components (a) and the chamber with all the components (b) for each source.

Interactions	Source					
	^{90}Sr/^{90}Y		^{85}Kr		^{147}Pm	
	Photons					
	a	b	a	b	a	b
Track entering	37,405	44,817	869	1048	5449	6015
Population	37,422	42,604	872	989	5459	5730
Collisions	7	20	1	3	2	1
Interactions	**Electrons**					
	a	b	a	b	a	b
Track entering	239,328	252,117	11,514	12,434	3681	2889
Population	248,439	252,296	12,336	12,212	3669	2850
Substeps	308,595	375,139	31,965	36,981	122	90

Table 3
Energy deposited by the radiation (MeV) in the cavity of the extrapolation chamber without considering the components (a) and in the chamber with all the components (b) for each source.

Source	**a**	**b**
^{90}Sr/^{90}Y	$(1.425 \pm 0.016) \times 10^{-6}$	$(1.670 \pm 0.017) \times 10^{-6}$
^{85}Kr	$(1.26 \pm 0.04) \times 10^{-7}$	$(1.54 \pm 0.03) \times 10^{-7}$
^{147}Pm	$(5.00 \pm 0.28) \times 10^{-8}$	$(4.21 \pm 0.26) \times 10^{-8}$

Table 4
PMMA backscattering factors and backscatter correction factors.

	Source		
Factor	^{90}Sr/^{90}Y	^{85}Kr	^{147}Pm
B_{PMMA}	1.172 ± 0.017	1.23 ± 0.05	0.84 ± 0.07
k_{ba} **Monte Carlo**	1.016 ± 0.022	1.02 ± 0.06	0.98 ± 0.12
k_{ba} **ISO**	1.010 ± 0.003	1.010 ± 0.003	1.000 ± 0.004
Difference (%)	0.6	0.9	2.04

Table 5
Interactions in the cavity of the extrapolation chamber with (1) and without (2) absorbers.

Interactions	**Source**					
	^{90}Sr/^{90}Y		^{85}Kr		^{147}Pm	
	Photons					
	1	2	1	2	1	2
Track entering	44,817	41,679	1048	863	6015	5941
Population	42,604	39,229	989	819	5730	5627
Collisions	20	6	3	1	1	2
Interactions	**Electrons**					
	1	2	1	2	1	2
Track entering	252,117	148	12,434	24	2889	0
Population	252,296	148	12,212	18	2850	0
Substeps	375,139	1355	36,981	112	90	0

the interactions in the chamber cavity (simulated with all the components) for the ^{90}Sr/ ^{90}Y and ^{85}Kr sources. In the same case, for the ^{147}Pm source, a decrease in the interactions in the chamber (simulated with all the components) is shown. The deposited energy is higher in the case of the presence of the PMMA backscatter for the sources of ^{90}Sr/^{90}Y and ^{85}Kr. In the case of the ^{147}Pm source, the energy deposited is lower in the presence of the PMMA backscatter (Table 3). These results are in agreement with the results obtained by Owen (1973) by means of the measurement method of the ionization currents considering the same conditions used in this work.

Table 4 shows the PMMA backscatter factors B_{PMMA} and the backscatter correction factors k_{ba} of the sources determined by Eqs. (1) and (3) respectively. The results are compared with the values of the factor k_{ba} presented in ISO (2004), and the differences between the factors determined by the Monte Carlo method and those of the ISO are also shown in Table 4.

The backscatter factors and the associated uncertainties presented in Table 4 are in agreement with the factors reported by the ISO standard (ISO, 2004) for all three sources. Other factors were determined by Owen (1973) for the ^{147}Pm source, and by Böhm (1986) for this source and also for the ^{85}Kr source. These factors are also in agreement with the results obtained in this work.

Table 5 shows a comparison of the interactions in the cavity of the extrapolation chamber with and without the absorbers, for each radiation source.

Fig. 3 shows a particle distribution simulation with and without the PMMA absorber in the case of the ^{90}Sr /^{90}Y source. For display purposes, only the distribution of 2000 particles can be observed. Fig. 3a shows the particle distribution with the PMMA absorber, and Figure b shows the distribution without absorber. Both figures show the particles distributed in air and in the main components of the extrapolation chamber; particularly the region corresponding to the sensitive volume is indicated.

The parameters in Table 5 and Fig. 3 clearly show a decrease in the interactions in the cavity when the absorbers are placed in front of the extrapolation chamber entrance window.

The Bremsstrahlung correction factor was determined by Eq. (4). The results of the Bremsstrahlung correction factors are shown in

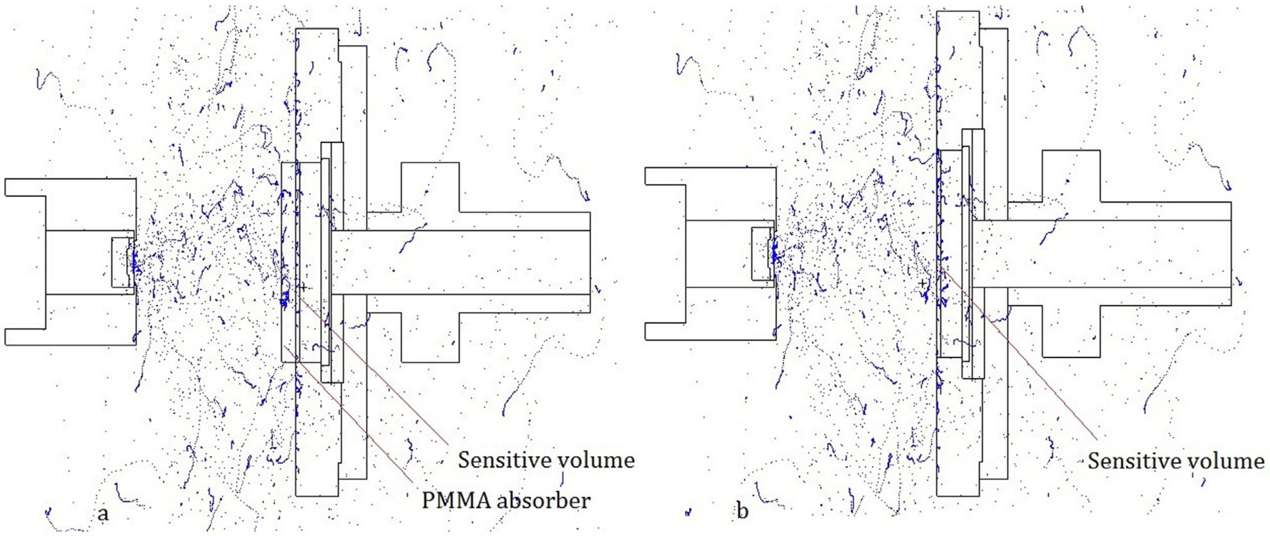

Fig. 3. Particle distribution simulation: a) with PMMA absorber; b) without PMMA absorber.

Table 6
Bremsstrahlung correction factors of the radiation sources determined by the Monte Carlo method.

Factor	Source		
	^{90}Sr/^{90}Y	^{85}Kr	^{147}Pm
k_{br} **Monte Carlo**	0.9975 ± 0.0004	0.9944 ± 0.0017	0.99997 ± 0.00003
k_{br} **ISO**	1.000 ± 0.002	1.000 ± 0.002	0.990 ± 0.002
Difference (%)	0.25	0.6	1

Table 6. The results are compared with the values of the factor k_{br} presented in ISO (2004), and the differences between the factors determined by the Monte Carlo method and those of the ISO are also shown in Table 6.

The Bremsstrahlung correction factors determined by the Monte Carlo method are in agreement with the values reported by ISO (2004). Although the Bremsstrahlung correction factors for the ^{147}Pm source presents a 1% difference in relation to the factor reported by ISO (2004), it is in agreement with the factors reported by Böhm (1986). According to this reference, the values are between (0.994 ± 0.002) and (0.998 ± 0.002).

4. Conclusions

The correction factors for the backscatter of the collecting electrode and guard ring, and the correction factors for Bremsstrahlung in the BSS2 beta radiation beams were determined by the Monte Carlo method.

The correction factors determined by Monte Carlo method are in agreement with those reported by ISO (2004).

The agreement of the results of the simulation and the factors reported by ISO (2004) shows that the results are suitable for the establishment of a primary standard for beta radiation.

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