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Monte Carlo modeling of a holder for irradiation of dosimeters in beta radiation beams

Ivón Oramas Polo[a,*], William Souza Santos[a,b], Linda V.E. Caldas[a]

[a] Instituto de Pesquisas Energéticas e Nucleares/Comissão Nacional de Energia Nuclear, IPEN/CNEN, Av. Prof. Lineu Prestes, 2242, 05508-000 São Paulo, SP, Brazil
[b] Universidade Federal de Uberlândia, Instituto de Física, Av. João Naves de Ávila, 2121, Santa Mônica, 38400-902 Uberlândia, MG, Brazil

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ABSTRACT

A study of the influence of a dosimetric holder and its cover for the irradiation of the dosimeters in the Beta Secondary Standard BSS2 radiation fields is reported. The correction factors for attenuation or scattering were calculated taking into account the BSS2 beta source energy, as well as the detector source distance. The study and the determination of these factors were carried out using the Monte Carlo Method. The results of the correction factors showed that the absorption and scattering of the electrons depend greatly on the energy of beta radionuclides. The determined correction factors are in agreement with the international report ISO 6980.

1. Introduction

External beta irradiation differs from the case of penetrating radiations such as gamma rays and neutrons, because cloths, gloves, etc., easily absorb beta radiation. Nevertheless, if the body parts are not well protected, severe damage may occur. Beta radiation is characterized by a rapid change in the dose rate with depth (Workshop, 1986).

Due to the short range of beta radiation, the detectors must be properly calibrated.

Beta radiation detectors are exposed to beams that uniformly irradiate the detector volume with the center used as a reference point. However, when the radioactive source distance to the detector volume is small, the radiation beam is not uniform. Likewise, low energy sources may cause that radiation in the detector volume not to be uniform due to radiation attenuation (Swinth et al., 1988; Behrens, 2013).

The response of the dosimeters not only presents a strong dependence on the energy of the beta emitter, but also depends on the irradiation geometry (Workshop, 1986).

The attenuation of beta radiation in matter can be described by an exponential function with a mass attenuation coefficient that is dependent on the maximum energy of the beta spectrum. The beta dose rate may increase in value when very thin absorbers are used. This does not happen only with radiation intense beams and monoenergetic electrons, but also with beta emitter beams. Beta particles are easily scattered in matter. Because of this scattering, the fluence of the beam through absorbers can be significantly altered (Caldas, 1980).

For radiological protection, both an increase in the dose rate due to backscattering and a variation in dosimeter measurement due to the presence of a backscatter located behind the dosimeter are of great importance (Caldas, 1980). Both attenuation and backscattering have to be taken into account in the calibration of detectors.

It is well known that the extrapolation chamber is the primary instrument for measuring beta radiation (Böhm, 1986). However, measurements with that instrument are made under laboratory conditions. In addition, this chamber is very heavy and its entrance window is very delicate. An alternative for beta dosimetry are thermoluminescence (TL) and optically stimulated thermoluminescence (OSL) techniques with different detectors. The TL and OSL dosimeters may constitute beta-radiation transfer systems.

In the Laboratory for Calibration of Instruments of IPEN (LCI/IPEN) there are two Beta Secondary Standard Systems for radiation protection: BSS1, Buchler GmbH & Co., Germany ($^{90}Sr/^{90}Y$, ^{204}Tl and ^{147}Pm sources) and BSS2, Isotrak, Germany ($^{90}Sr/^{90}Y$, ^{85}Kr and ^{147}Pm sources). These systems produce standard beta radiation beams for calibration and determination of dose or dose rate of detectors. The main differences between these systems are the substitution of the source of ^{204}Tl by the source of ^{85}Kr and the addition of a control unit operating with a software and a hardware, which control the type of beta source, the source-detector distance, the incident radiation angle and the presence of the beam flattening-filter (Ambrosi et al., 2007). For the calibration and establishment of a beta-radiation transfer

* Corresponding author.
E-mail addresses: ivonoramas67@gmail.com (I.O. Polo), willithan@yahoo.com.br (W.S. Santos), lcaldas@ipen.br (L.V.E. Caldas).

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system in the LCI/IPEN, the dosimeters are irradiated with the Beta Secondary Standard (BSS2) system using a Polymethyl methacrylate (PMMA) holder with a cover. This cover must be as thin as possible to allow the transmission of the beta particles. Depending on the beta radiation energy, the beta particles may be attenuated or more or less scattered by the Hostaphan (Polyethylene terephthalate (PET)) sheet cover and the holder. This could cause an increase or a decrease of the absorbed dose. To compensate for these discrepancies, a correction factor must be determined to obtain the actual absorbed dose.

In recent years, the beta radiation standard BSS2 has been simulated using the Monte Carlo techniques. Behrens (2013) determined the electron and photon spectra of the BSS2 system, and the angular distributions and depth dose profiles were given. Faria et al. (2015) obtained the transmission factors and absorbed dose rates in tissue for BSS2 beta radiation fields from $^{90}Sr/^{90}Y$ and ^{85}Kr sources. A comparison of the parameters for $^{90}Sr/^{90}Y$ and ^{147}Pm radiation fields produced by the BSS1 and BSS2 systems, using the Monte Carlo method was performed at the Atomic Energy Agency in Japan (Yoshotomi et al., 2014). The influence of these irradiation systems on the calibration of dosimeters was investigated later (Yoshotomi and Kowatari, 2016).

The aim of this work was to study the influence of the holder and the cover for the irradiation of the dosimeters in the absorbed dose. Based on this study, the correction factors for attenuation or scattering were calculated taking into account the beta source energy, as well as the detector source distance. The study and the determination of these factors were carried out using the Monte Carlo method.

2. Material and methods

2.1. Beta radiation sources

In order to determine the influence of the holder and the cover for the irradiation of the dosimeters, the LCI/IPEN BSS2 sources were used. The main characteristics of these sources are shown in Table 1 (BSS2, 2005; PTB, 2005a, 2005b, 2005c). For the ^{85}Kr and ^{147}Pm sources, as well as for the $^{90}Sr/^{90}Y$ source at 30 cm of detector source distance, a Polyethylene terephthalate (Hostaphan) beam-flattening filter must be used (BSS2, 2005; Ambrosi et al., 2007).

Additional simulations were performed at distances of 11 cm, 20 cm and 50 cm using the beam flattening-filter, with the aim of comparisons with the standard distances.

2.2. Dosimeters and holder

The dosemeters were considered as radiation detectors with the following characteristics: (4.59 ± 0.01) mm diameter, (1.119 ± 0.010) mm thickness and (51.8 ± 0.4) mg mass. According to the manufacturer, the SOL-GEL α-Al_2O_3 detectors present the following impurities: (895.5 ± 44.8) ppm (C), (310.0 ± 30.6) ppm (Ca), (99.8 ± 9.9) ppm (Fe), (31.5 ± 3.2) ppm (Cr), (5.0 ± 0.3) ppm (Mo), (25.0 ± 2.5) ppm (Ni) and (0.9 ± 0.1) ppm (Mg) (Ferreira and Santos, 2014).

Table 1
Main characteristics of the BSS2 beta sources.

Characteristic	Radionuclide		
	^{147}Pm	^{85}Kr	^{90}Sr/^{90}Y
Nominal activity (GBq)	3.7	3.7	0.46
Mean; maximum beta energy (MeV)	0.06; 0.23	0.24; 0.69	0.8; 2.3
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

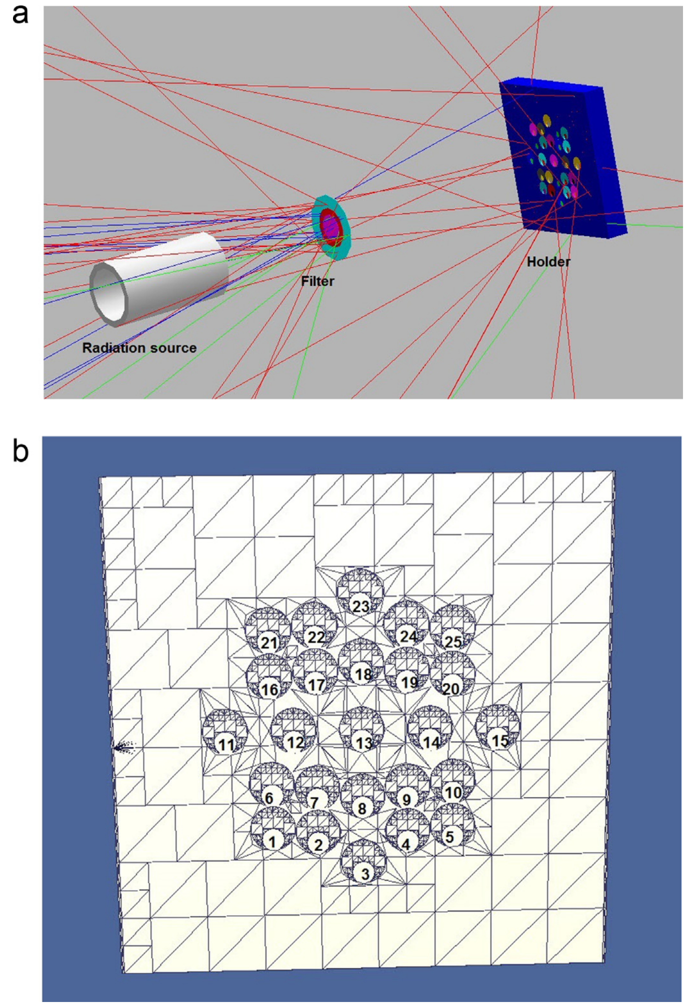

Fig. 1. a) Geometrical MCNP model for the BSS2 system; b) Model of irradiation holder with dosimeter numbers.

The irradiation holder is made of Polymethyl methacrylate (PMMA), and it has the following dimensions: 110 mm × 110 mm × 18 mm. The holder allows the simultaneous irradiation of 25 dosimeters, and the holder cover is made of a Hostaphan sheet of 0.015 mm of thickness. The dosimeters were positioned from the bottom, left at the holder, in groups of five samples in each row. For example, in the first lower row were positioned the dosimeters from number 1 to number 5.

2.3. MCNP5 model of holder and radiation sources

The Monte Carlo code MCNP5 was used in coupled electron–photon physics mode to study the influence of the holder and the cover for the irradiation of the dosimeters in the absorbed dose, and to determine the correction factors for attenuation or scattering. The Monte Carlo code MCNP5 allows the modeling of complex geometries and is widely used in dosimetry applications. For electron transport, a continuous-slowing-down model that includes positrons, x-rays, and bremsstrahlung is used (MCNP5, 2008).

A geometrical MCNP model for the BSS2 system used in the study is shown in Fig. 1a as an example. Fig. 1b shows the MCNP model of the Polymethyl methacrylate (PMMA) holder with the SOL-GEL α-Al_2O_3 dosimeters. For the simulations, the actual dimensions of the holder with the hollows to place the dosimeters were considered. The chemical composition of the dosimeters was considered taking into account the producer's information (Ferreira and Santos, 2014).

Table 2
Population of electrons for the simulation of the holder and the cover with the dosimeters.

Radionuclide									
$^{90}Sr/^{90}Y$								^{85}Kr	^{147}Pm
Source-detector distance (cm)									
11	20	30	30 (Filter)	50	11 (Filter)	20 (Filter)	50 (Filter)	30	20
6,137,556	7,474,272	7,457,434	7,456,978	7,455,975	5,634,925	6,387,498	3,724,934	145,407	1380

Table 3
Population of electrons for the simulation of dosimeters without the holder and without the cover.

Radionuclide									
$^{90}Sr/^{90}Y$								^{85}Kr	^{147}Pm
Source-detector distance (cm)									
11	20	30	30 (Filter)	50	11 (Filter)	20 (Filter)	50 (Filter)	30	20
5,817,141	7,284,494	7,268,473	7,267,525	7,266,642	5,327,537	6,087,542	3,638,018	159,022	2853

Table 4
Fraction of absorbed or scattered beta particles according to the energy of the radiation source.

Radionuclide									
$^{90}Sr/^{90}Y$								^{85}Kr	^{147}Pm
Source-detector distance (cm)									
11	20	30	30 (Filter)	50	11 (Filter)	20 (Filter)	50 (Filter)	30	20
7,69%	6,10%	6,11%	6,09%	6,09%	6,77%	7,27%	6,11%	3,78%	12,51%

Table 5
Correction factors for attenuation or scattering in beta radiation (Standard BSS2 calibration source-detector distances).

Dosimeter number	Radionuclide						
	$^{90}Sr/^{90}Y$					^{85}Kr	^{147}Pm
	Source-detector distance (cm)						
	11	20	30	30 (Filter)	50	30	20
1	0.950 ± 0.020	0.965 ± 0.017	0.965 ± 0.017	0.965 ± 0.017	0.965 ± 0.017	1.14 ± 0.14	1.80 ± 0.29
2	0.941 ± 0.020	0.967 ± 0.017	0.967 ± 0.017	0.968 ± 0.017	0.968 ± 0.017	1.13 ± 0.15	2.0 ± 0.3
3	0.943 ± 0.020	0.972 ± 0.017	0.973 ± 0.017	0.973 ± 0.017	0.973 ± 0.017	1.05 ± 0.14	1.9 ± 0.3
4	0.937 ± 0.019	0.985 ± 0.017	0.985 ± 0.017	0.985 ± 0.017	0.986 ± 0.017	1.07 ± 0.14	2.2 ± 0.4
5	0.929 ± 0.020	0.978 ± 0.017	0.979 ± 0.017	0.979 ± 0.017	0.979 ± 0.017	1.11 ± 0.14	2.0 ± 0.3
6	0.966 ± 0.020	0.965 ± 0.017	0.965 ± 0.017	0.965 ± 0.017	0.965 ± 0.017	1.13 ± 0.14	2.4 ± 0.4
7	0.967 ± 0.019	0.979 ± 0.017	0.979 ± 0.017	0.980 ± 0.017	0.980 ± 0.017	1.05 ± 0.13	2.0 ± 0.3
8	0.957 ± 0.019	0.980 ± 0.017	0.980 ± 0.017	0.981 ± 0.017	0.981 ± 0.017	1.13 ± 0.15	2.2 ± 0.4
9	0.977 ± 0.019	0.973 ± 0.017	0.972 ± 0.017	0.972 ± 0.017	0.972 ± 0.017	1.03 ± 0.12	1.76 ± 0.28
10	0.947 ± 0.019	0.983 ± 0.017	0.983 ± 0.017	0.984 ± 0.017	0.984 ± 0.017	1.17 ± 0.15	1.91 ± 0.29
11	0.945 ± 0.020	0.959 ± 0.017	0.959 ± 0.017	0.959 ± 0.017	0.959 ± 0.017	1.12 ± 0.14	2.1 ± 0.3
12	0.945 ± 0.019	0.976 ± 0.017	0.975 ± 0.017	0.976 ± 0.017	0.976 ± 0.017	1.06 ± 0.14	2.1 ± 0.4
13	0.964 ± 0.019	0.970 ± 0.016	0.970 ± 0.016	0.970 ± 0.016	0.971 ± 0.017	1.08 ± 0.14	2.4 ± 0.5
14	0.947 ± 0.019	0.975 ± 0.017	0.975 ± 0.017	0.975 ± 0.017	0.975 ± 0.017	1.14 ± 0.15	1.86 ± 0.29
15	0.934 ± 0.019	0.966 ± 0.017	0.966 ± 0.017	0.966 ± 0.017	0.966 ± 0.017	1.04 ± 0.14	2.6 ± 0.5
16	0.945 ± 0.019	0.975 ± 0.017	0.975 ± 0.017	0.974 ± 0.017	0.974 ± 0.017	1.16 ± 0.15	1.9 ± 0.3
17	0.932 ± 0.019	0.979 ± 0.017	0.979 ± 0.017	0.978 ± 0.017	0.978 ± 0.017	1.00 ± 0.13	2.1 ± 0.4
18	0.927 ± 0.018	0.974 ± 0.017	0.974 ± 0.017	0.975 ± 0.017	0.975 ± 0.017	1.13 ± 0.14	2.0 ± 0.4
19	0.956 ± 0.019	0.964 ± 0.016	0.964 ± 0.017	0.965 ± 0.017	0.965 ± 0.017	1.15 ± 0.15	1.89 ± 0.28
20	0.933 ± 0.019	0.955 ± 0.016	0.954 ± 0.016	0.954 ± 0.016	0.954 ± 0.016	1.08 ± 0.14	2.3 ± 0.4
21	0.967 ± 0.020	0.974 ± 0.017	0.974 ± 0.017	0.973 ± 0.017	0.973 ± 0.017	1.04 ± 0.14	2.4 ± 0.4
22	0.962 ± 0.020	0.990 ± 0.017	0.989 ± 0.017	0.989 ± 0.017	0.989 ± 0.017	1.03 ± 0.14	1.9 ± 0.3
23	0.944 ± 0.020	0.975 ± 0.017	0.976 ± 0.017	0.975 ± 0.017	0.975 ± 0.017	1.10 ± 0.14	2.1 ± 0.4
24	0.958 ± 0.019	0.993 ± 0.017	0.993 ± 0.017	0.993 ± 0.017	0.993 ± 0.017	1.05 ± 0.12	2.0 ± 0.3
25	0.957 ± 0.020	0.976 ± 0.017	0.975 ± 0.017	0.975 ± 0.017	0.975 ± 0.017	1.08 ± 0.13	2.4 ± 0.4

The material densities used in the simulations for Mylar, acrylic, aluminum, steel, silver, Kr, Pm_2O_3, $SrCO_3$ and air were 1.38, 1.19, 2.85, 8.06, 10.5, 0.0191, 6.85, 3.76 and 1.205×10^{-3} g/cm^3, respectively (ICRU, 1997).

Exposures of the dosimeters to BSS2 sources were modelled. The actual dimensions of the radiation sources, including their shielding, were considered. The energy spectra of the sources used in the simulations were taken based on the ICRU Report No.56 (ICRU, 1997). The dosimeters were considered as cells in the MCNP simulations.

To study the influence of the holder and the cover for the irradiation

Table 6
Correction factors for scattering in beta radiation ($^{90}Sr/^{90}Y$ source for distances 11 cm, 20 cm and 50 cm with beam flattening filter).

Dosimeter number	Source-detector distance (cm)		
	11	20	50
1	0.949 ± 0.019	0.957 ± 0.019	0.981 ± 0.025
2	0.923 ± 0.020	0.954 ± 0.019	0.978 ± 0.024
3	0.942 ± 0.019	0.951 ± 0.019	0.963 ± 0.024
4	0.921 ± 0.020	0.950 ± 0.019	0.986 ± 0.024
5	0.932 ± 0.019	0.959 ± 0.019	0.976 ± 0.024
6	0.956 ± 0.022	0.967 ± 0.019	0.971 ± 0.024
7	0.947 ± 0.020	0.969 ± 0.019	0.978 ± 0.024
8	0.926 ± 0.020	0.960 ± 0.019	0.981 ± 0.024
9	0.949 ± 0.020	0.967 ± 0.019	0.986 ± 0.024
10	0.923 ± 0.021	0.984 ± 0.019	0.996 ± 0.025
11	0.955 ± 0.019	0.931 ± 0.019	0.961 ± 0.024
12	0.934 ± 0.020	0.951 ± 0.019	0.979 ± 0.024
13	0.954 ± 0.022	0.967 ± 0.019	0.960 ± 0.023
14	0.938 ± 0.020	0.941 ± 0.018	0.975 ± 0.024
15	0.950 ± 0.019	0.933 ± 0.019	0.967 ± 0.024
16	0.931 ± 0.020	0.948 ± 0.019	0.978 ± 0.024
17	0.958 ± 0.021	0.944 ± 0.018	0.966 ± 0.023
18	0.961 ± 0.022	0.951 ± 0.018	1.000 ± 0.024
19	0.949 ± 0.021	0.945 ± 0.018	0.966 ± 0.023
20	0.948 ± 0.021	0.956 ± 0.019	0.958 ± 0.023
21	0.971 ± 0.021	0.970 ± 0.019	0.975 ± 0.024
22	0.952 ± 0.021	0.963 ± 0.019	0.981 ± 0.024
23	0.969 ± 0.021	0.940 ± 0.019	0.978 ± 0.024
24	0.972 ± 0.021	0.960 ± 0.019	0.982 ± 0.024
25	0.959 ± 0.020	0.953 ± 0.019	0.975 ± 0.024

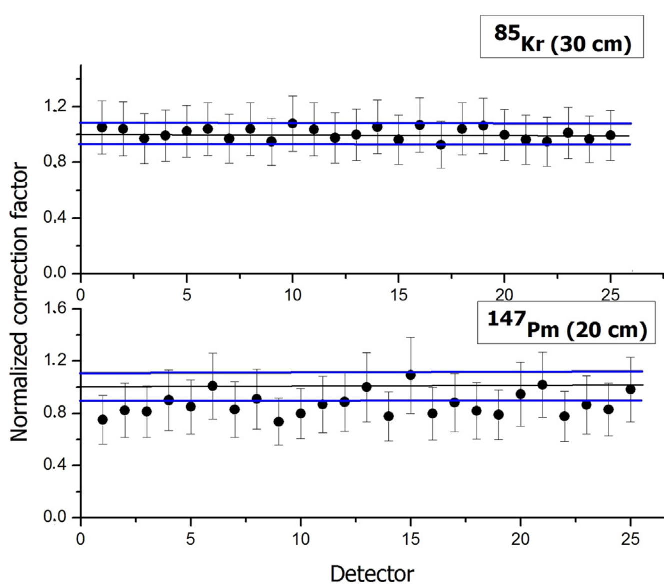

Fig. 2. Normalized correction factors in the dosimeter holder for the ^{85}Kr and the ^{147}Pm sources at the source-detector distances of 30 cm and 20 cm, respectively. The blue lines indicate the limits established by ISO 980–1(2006). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

of the dosimeters, and to determine the correction factors for attenuation or scattering, three types of detailed simulations were used: Simulation of the holder and the cover with the dosimeters; Simulation of the holder with the dosimeters without the cover; and Simulation of the dosimeters without the holder and without the cover. In this way, it is possible to quantify the energy deposited in the volume of the dosimeters through the MCNP5 *tally* * f8 (in MeV) in all the simulations for all three BSS2 radiation sources. All of the established calibration distances were considered.

According to the ISO (6980)-1 (2006), the absorbed dose is the quotient of the energy imparted E by the ionizing radiation to a matter of mass m. By means of the simulation by Monte Carlo method, it is possible to determine the energy deposited in each detector of mass m. Taking into account that the mass of the detector is constant, it is possible to determine the number of particles that were absorbed, in case of ^{85}Kr and ^{147}Pm, or scattered, in case of $^{90}Sr/^{90}Y$, by the holder, using the following expression:

$$k_h = E_{without\_hc}/E_{without\_c} * \quad 100 \tag{1}$$

where $E_{without\_c}$ is the energy deposited (MeV) by the radiation without the cover and $E_{without\_hc}$ is the deposited energy (MeV) by the radiation without both holder and cover.

For the determination of the correction factors, the following expression was used:

$$k_c = E_{without\_hc}/E_{whc} \tag{2}$$

where E_{whc} is the energy deposited (MeV) by the radiation in the dosimeter considering the holder and the cover.

According to the ISO (6980)-1 (2006) and Ambrosi et al. (2007), in the BSS2 system to produce a uniform dose over a minimum area of 15 cm in diameter, at the calibration distance, the variation in the dose rate should be less than ± 5% for $^{90}Sr/^{90}Y$ and ^{85}Kr and less than ± 10% for ^{147}Pm. Once the correction factors have been determined, they will be normalized with the value obtained at the center of the beam. The normalized values must be within the requirements established by the international report ISO (6980)-1 (2006).

3. Results and discussion

Based on the design of Fig. 1, the MCNP was performed until reaching 10^8 particle histories in all geometric configurations to ensure an acceptable statistical uncertainties. On average, the typical CPU time of the simulations ranged from 5 h to 8 h on an Intel Core i7 processor microcomputer with 16 GB of RAM. The improved electron transport algorithm of ITS (Integrated Tiger Series) for electron transport was used.

Tables 2 and 3 show a comparison between the total population of electrons for the simulation of the holder and the cover with the dosimeters, and for the simulation of dosimeters without the holder and the cover, respectively.

Both Tables 2 and 3 show the population of electrons taking into account the BSS2 radiation source type and the source-detector distance.

In the case of the $^{90}Sr/^{90}Y$ source, for the distance of 11 cm, the electron population is lower than for other distances due to the divergence of the beta particles. The population of electrons decreased as the source-detector distance increased, and in the case of the presence of the beam-flattening filter, a decrease was observed due to the absorption caused by this filter. For the ^{85}Kr and ^{147}Pm sources, the population of electrons decreased notably due to the lower energy of these radionuclides (See Table 1).

Both Tables 2 and 3 show that depending on the beta radiation energy, the particles are absorbed by the cover and by the holder in the case of ^{85}Kr and ^{147}Pm sources. A large fraction of low energy from ^{147}Pm source was scattered and absorbed in air and in the beam-flattening filter. In the case of ^{85}Kr source, the fraction is smaller. On the other hand, the high-energy beta radiation of $^{90}Sr/^{90}Y$ source is scattered by the cover and the holder and presenting thus a build-up phenomenon of absorbed dose. As the source-detector distance increased for this source, the population of electrons decreased, and in the case of the beam-flattening filter use, there was a decrease in this population. For the 11 cm source-detector distance, the radiation field was not uniform due to the divergence of the particles, and the population of electrons was lower than for the previous cases, with the $^{90}Sr/^{90}Y$ source.

Table 4 shows the fraction of the beta particles that were absorbed

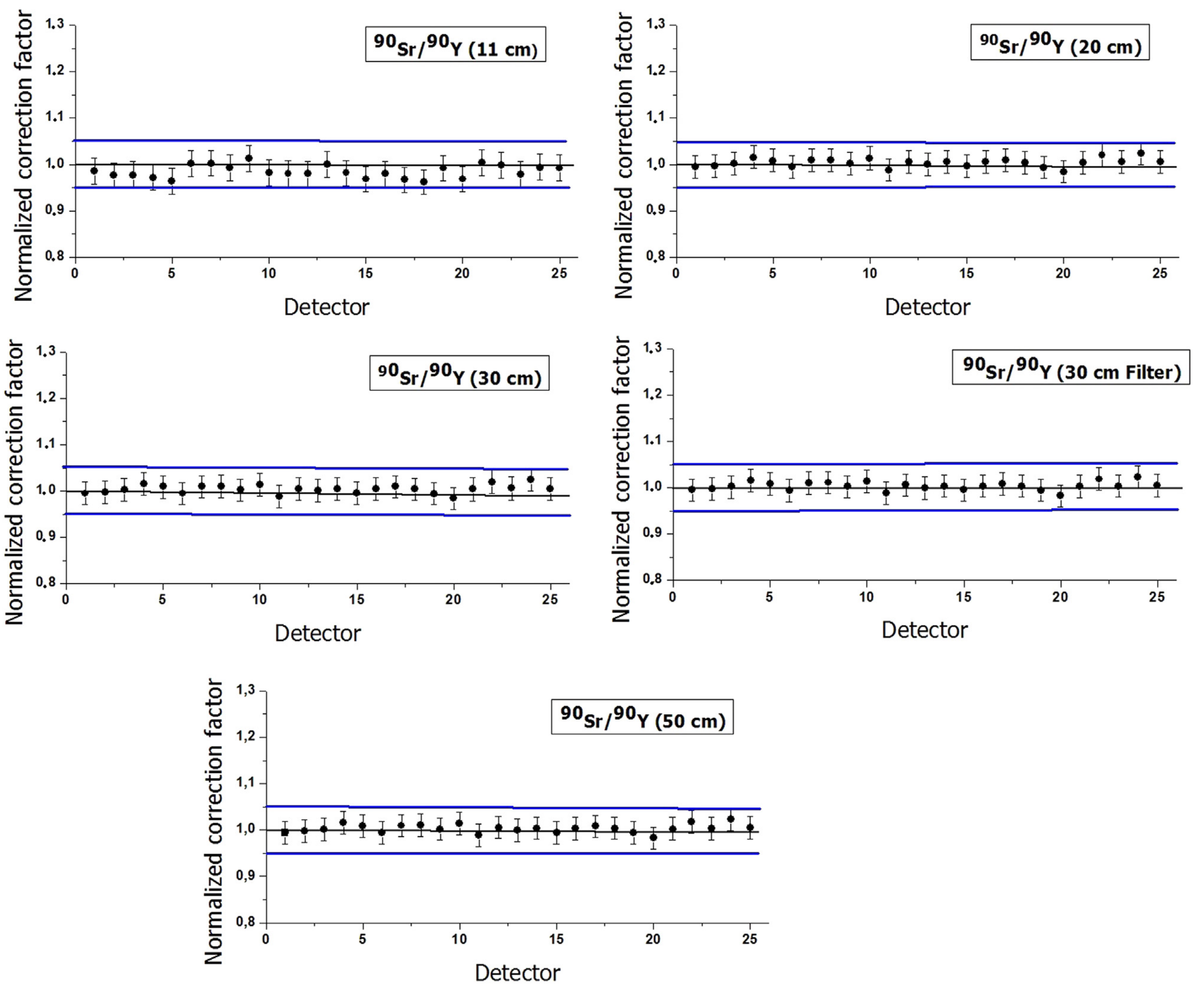

Fig. 3. Normalized correction factors in the dosimeter holder for the $^{90}Sr/^{90}Y$ source at the source-detector distance of 11 cm, 20 cm, 30 cm, 30 cm with filter and 50 cm (Standard BSS2 calibration source-detector distances). The blue lines indicate the limits established by ISO (6980)-1 (2006). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

or scattered taking into account the source energy and the use of beam flattening filter. This fraction was calculated using Eq. (1). The results show that for the $^{90}Sr/^{90}Y$ source, the beam flattening filter caused an absorption in the case of the distance of 11 cm, and in the case of distances of 20 cm and 50 cm, a scattering occurred. For the ^{85}Kr and ^{147}Pm sources, the fraction of particles that were absorbed by the holder is shown. There are significant differences between the results for these sources, due to the mentioned characteristics of the ^{147}Pm low energy source.

Finally, the correction factors for attenuation or scattered beta radiation were determined by Eq. (2). Tables 5 and 6 show the results obtained for these factors.

There were no large differences among the correction factors of the $^{90}Sr/^{90}Y$ source for the detector-source distances of 20 cm, 30 cm with and without filter, and 50 cm. For the distance of 11 cm with this source, a slight difference can be seen with respect to the other distances. For the ^{85}Kr and ^{147}Pm sources, the correction factors again demonstrate the loss of energy due to absorption in the air and in the beam-flattening filters. The results of the correction factors clearly show that the absorption and the scattering of the electrons depend greatly on the energy of these beta radionuclides.

The values of the correction factors were normalized to the value obtained at the center of the beam. This value corresponds to the position of the dosimeter number 13 (See Fig. 1b). Figs. 2–4 show the distribution of the normalized correction factors in the dosimeter holder for all the simulations carried out. The limits established by the ISO (6980)-1 (2006) are represented by blue lines, and it can be seen that all the values of the correction factors are in agreement with the requirements of this standard. A similar result from these sources was reported by Behrens (2013) in the simulation of the radiation fields of the Beta Secondary Standard BSS 2.

Following the procedure of Ambrosi et al. (2007), the normalized mean values of the correction factors of the detectors covering an area of 30 mm × 30 mm were compared with similar values reported for a Physikalisch-Technische Bundesanstalt (PTB) primary extrapolation chamber (30 mm collecting electrode). The values correspond to the calibration distances established as standards for the BSS2 system. The results are shown in Table 7. The values of the correction factors are in good agreement with the limits established by the ISO (6980)-1 (2006) and with the normalized values of the extrapolation chamber of Ambrosi et al. (2007).

4. Conclusions

The influence of the holder and the cover, for the irradiation of dosimeters, in the absorbed dose, using Monte Carlo method was

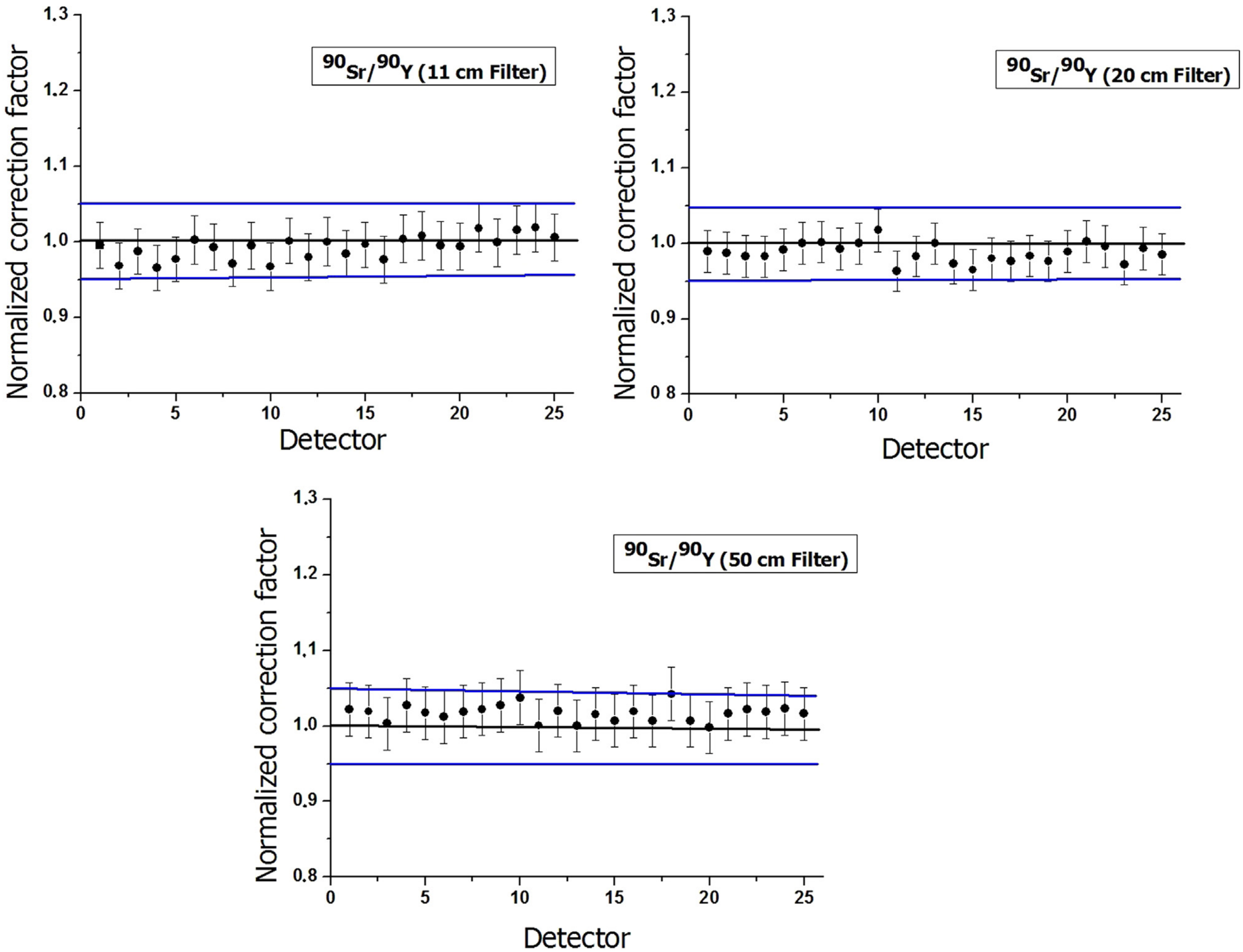

Fig. 4. Normalized correction factors in the dosimeters holder for the $^{90}Sr/^{90}Y$ source at the source-detector distance of 11 cm, 20 cm and 50 cm with filter (Not standard BSS2 calibration source-detector distances). The blue lines indicate the limits established by ISO (6980)-1 (2006). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Table 7
Normalized mean values of the correction factors for two areas of 30 mm × 30 mm for the standard BSS2 calibration source-detector distances and extrapolation chamber.

Standard BSS2 calibration source-detector distance	Normalized values	
	Detectors covering an area of 30 mm × 30 mm	Extrapolation chamber (Ambrosi et al., 2007)
$^{90}Sr/^{90}Y$, 11 cm, w/o filter	0.988 ± 0.006	0.999 ± 0.011
$^{90}Sr/^{90}Y$, 20 cm, w/o filter	1.0043 ± 0.0017	0.995 ± 0.008
$^{90}Sr/^{90}Y$, 30 cm, w/o filter	1.0040 ± 0.0017	0.997 ± 0.009
$^{90}Sr/^{90}Y$, 30 cm, with filter	1.0045 ± 0.0017	1.002 ± 0.005
$^{90}Sr/^{90}Y$, 50 cm, w/o filter	1.0044 ± 0.0017	0.996 ± 0.007
^{85}Kr, 30 cm, with filter	1.002 ± 0.016	1.000 ± 0.001
^{147}Pm, 20 cm, with filter	0.847 ± 0.057	1.001 ± 0.008

determined. The correction factors for attenuation or scattering were calculated taking into account the BSS2 beta source energies, as well as the detector source distance. The correction factors determined clearly show that the absorption and the scattering of the electrons in the holder and the cover, depending significantly on the energy of beta radionuclides. The values of the correction factors complied the requirements of the international report ISO 6980. The results can be applied for the calibration and establishment of a beta-radiation transfer system in the Laboratory for Calibration of Instruments of IPEN.

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