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Monte Carlo validation of the irradiator parameters of the Portuguese gamma irradiation facility after its replenishment

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A B S T R A C T

In December 2003 the irradiator of the Portuguese ^{60}Co irradiation facility, UTR, was replenished. Monte Carlo simulation studies were used to characterize the facility. Comparison of simulation results with experimental measurements were useful in estimating where the source elements were positioned and what the total activity was. For this purpose the MCNPX code was used. From the experimental point of view ionization chambers and PMMA dosemeters were used.

The results indicate that the geometry of the irradiator used for simulation studies shows a shift on the vertical dimension relative to the actual geometry of approximately 8 cm, but with reduced influence on the irradiation process. Considering the uncertainties of the experimental and simulated approaches the activity of the irradiator stated by supplier has been confirmed.

1. Introduction

Radiation processing has become a well-accepted technology on the global market with a wide variety of applications that range from sterilization of medical devices to irradiation of selected food items. In order to increase the knowledge about the irradiation facility, Monte Carlo simulation studies of the irradiation process can be carried out. These simulation studies should mimic as exactly as possible all the relevant parts of the irradiation room, in particular the irradiator, as well as the product to be irradiated and the source product irradiation geometry (Biju et al., 2008).

In December 2003 the irradiator of the Portuguese ^{60}Co irradiation facility, UTR, was replenished. Eighteen new sources were loaded and the older ones (156) were rearranged. The result was an irradiator with 10.2 PBq of total activity. The uncertainty associated with the activity of each source is not more than 5%, according to the manufacturer.

When the replenishment occurs (and also when a new irradiator is installed) it is not possible to check the irradiator details, namely its geometry and homogeneity, individual sources dimension and distribution inside the irradiator and the total activity installed. Due to these reasons, the commissioning of gamma irradiation facilities is normally based on experimental data.

The objective of this work is to validate the irradiator, namely its geometry and actual activity. For this purpose the Monte Carlo method is used. In fact, several studies of the UTR have already been performed with the MCNP Monte Carlo code before the recent replenishment (Oliveira et al., 2000a,b,c, 2002; Oliveira and Salgado, 2001). Thus the same methodology is applied in these new conditions.

2. Materials and methods

The methodology adopted to validate the new irradiator configuration is based on the comparison between the experimental dose rate measurements inside the irradiation room and Monte Carlo calculated dose rates.

Two important sets of data were obtained in the irradiation room. One set has been obtained on the plane parallel to the irradiator, in front of it. For this purpose ninety Harwell PMMA Red 4034 dosimeters (recommended dose range from 5 to 50 kGy and measurement reproducibility below 2%) were put on a card board fixed at the irradiator protection grid located at 6 cm from the irradiator, and irradiated for 1 h. The dosimeters were distributed in 6 vertical columns and 15 horizontal rows covering an area of 140 cm height by 120 cm wide. The equivalent setup was simulated with MCNPX Monte Carlo Code.

A second set of data were obtained at discrete positions inside the irradiation room. For this set the experimental measurements and corresponding simulations were done for two situations: with the irradiation room filled with boxes of material being irradiated in carriers suspended from a monorail conveyor (Oliveira et al.,

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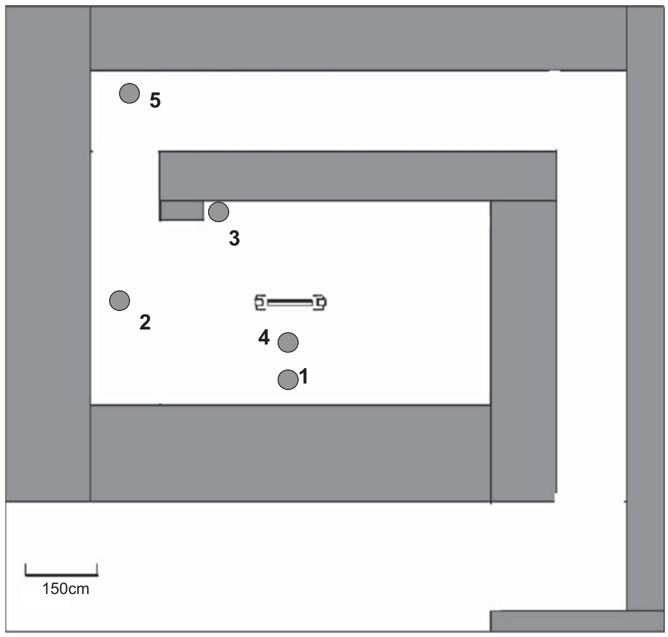

Fig. 1. Schematic representation of the irradiation room without boxes, showing the irradiator and the positions where tests were done.

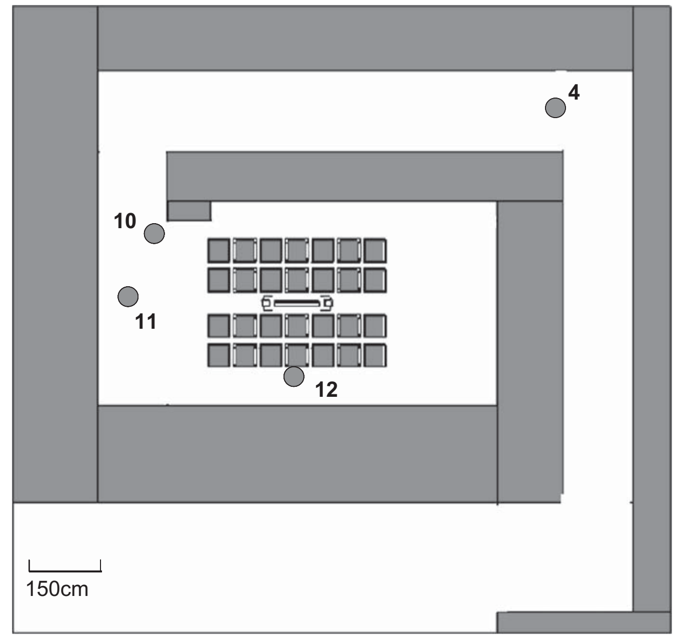

Fig. 2. Schematic representation of the irradiation room with the boxes, showing the irradiator and the positions where tests were done.

2000a,b,c) (dummy boxes with cork stoppers), and empty (all carriers were removed from the irradiation room). These experimental measurements were made using two different methods. For the empty irradiation room, two PTW ionizing chambers, models 23332 (0.3 cm^3 volume, for positions 1–4 in Fig. 1) and 23361 (30 cm^3 volume, for position 5 in Fig. 1) were used. Both ionization chambers were calibrated at the Laboratory for Ionizing Radiation Metrology (LMRI) of ITN, and traceable to the ^{60}Co ITN air-kerma primary standard. The measurements were made at 1 m height, except for point 4, which was at 1.5 m height.

For the measurements in the filled irradiation room the Harwell PMMA YR Gammachrome dosimeters were used (recommended dose range from 0.1 to 3 kGy and measurement reproducibility below 3%). The absorbed doses were determined experimentally at the positions 10, 11 and 12, as shown in Fig. 2. For each location three dosimeters were irradiated simultaneously at two different heights in a wood structure: 130 and 173.5 cm from the floor.

The discrete positions are shown in Figs. 1 and 2, for the empty and the non-empty irradiation room, respectively. For both cases the equivalent setups were simulated with MCNPX Monte Carlo Code.

Additionally for the empty irradiation room, simulation results were also calculated considering the irradiator was lowered 15 cm from its initial position.

The facility description in MCNP had been done previously (Oliveira et al., 2000a–c) and in this work the new irradiator configuration was considered in the input routine. In this study the MCNPX version 2.6 was used (MCNPX User's Manual, 2008). The calculations were performed in a PC with a Pentium M 760 (2.0 GHz) processor and 1 GB of RAM.

The gamma sources were modelled according to the data available by supplier and flux distribution and energy deposition (kerma approximation) by radiation in the volumes of interest have been calculated using the F4 and F6 specific MCNPX tally card (Portugal, 2008). All activities and dose rates are referred to 1st December 2003.

The MCNPX photon detailed model is used. This model includes coherent (Thomson) scattering and accounts for fluorescent photons after photoelectric absorption. Form factors are used with coherent and incoherent scattering to account for electron binding effects. Analog capture is always used. Relative to the electrons the Thick-Target Bremsstrahlung model (TTB) is used. This model generates electrons but assumes that they are locally slowed to rest. Any bremsstrahlung photons produced by the nontransported electrons are then banked for later transport (Portugal, 2008).

3. Results and discussion

The irradiator of the Portuguese ^{60}Co irradiation facility, UTR, was replenished but the remainder facility and irradiation process are unchanged and both have been previously described elsewhere (Mendes et al., 1990; Andrade et al., 1995; Cavaco et al., 1991). In Fig. 3(a) and (b) the activity distributions before and after replenishment can be seen.

3.1. Dose mapping in front of the irradiator

A dose mapping on a plane in front of the irradiator was made to check the new source distributions. At the time it was noticed that some degree of folding (particularly on the right side) had occurred due to the sliding of the card board's top fixation. In consequence, the dosimeters were in lower positions than initially expected. This sliding can be estimated as a shift of 4 cm maximum. Using the point kriging data interpolation method (Surfer® 7 User's Guide, 1999) the plot in Fig. 4a was obtained. Kriging is a geostatistical gridding method, which attempts to express trends suggested in the provided data.

The equivalent initial setup (without the sliding) was later simulated in MCNPX and, also using the kriging data interpolation method, the plot in Fig. 4b is obtained.

In both cases, the values below 5 kGy have been discarded. This is due to the recommended range of Red 4034 dosimeters as referred in Section 2. Thus, only sixty-seven dosimeters were considered for the plotting, mainly covering the area of most

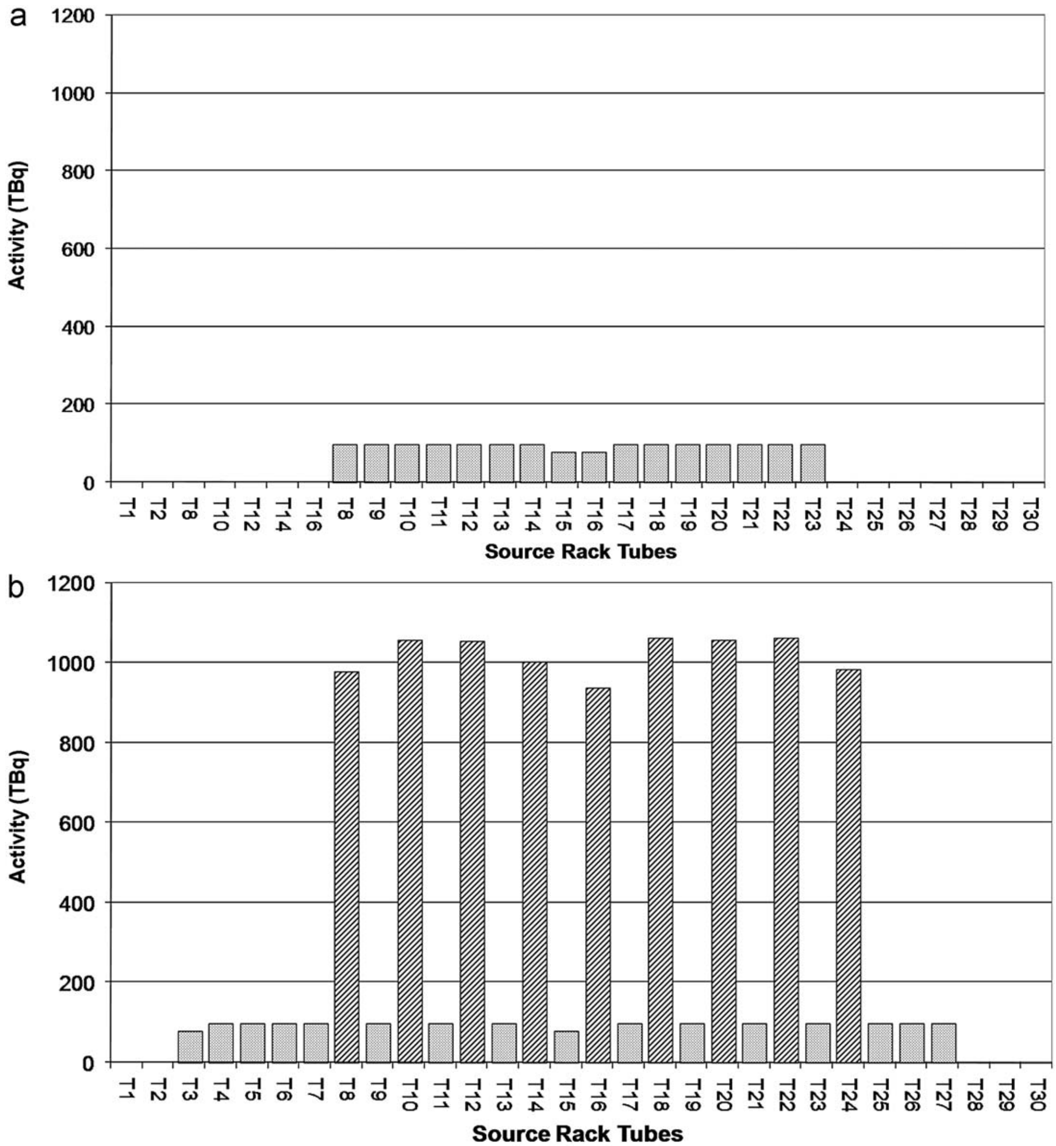

Fig. 3. (a) Activity distribution before replenishment (November 2003). (b) Activity distribution after replenishment (December 2003).

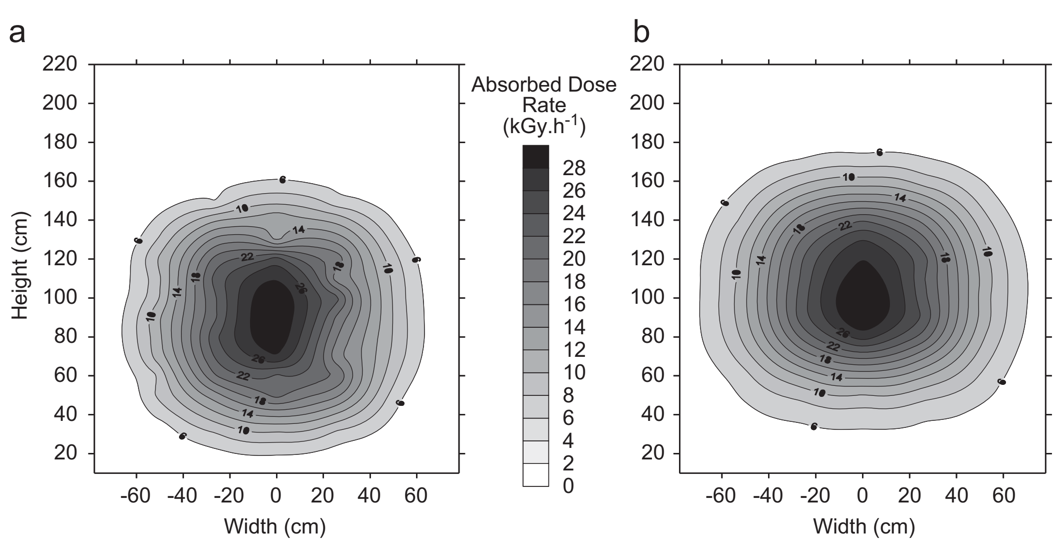

Fig. 4. (a) Experimental 2D mapping of the dose distribution in PMMA Red 4034 dosimeters at 6 cm from the irradiator. (b) Calculated 2D mapping of the dose distribution in simulated PMMA dosimeters at 6 cm from the irradiator.

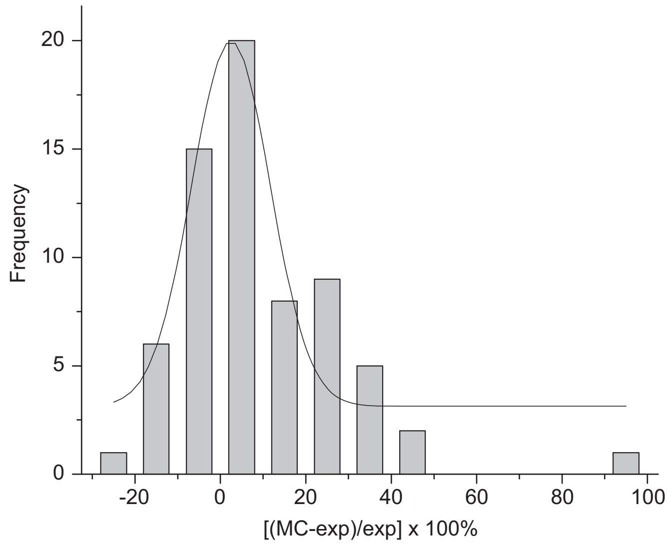

Fig. 5. Frequency histogram of the percentage of deviation of the simulation (MC) results of the dose mapping from the experimental (exp) ones.

interest: the irradiator projection on the mapping plane. The results presented are referred to as December 2003.

Due to the spatial distribution of the sources and correspondent activity distribution in the irradiator (see Fig. 3b) it was expectable that the isodose surfaces should show a tendency to the spherical shape as the distance to the source increases. In truth, when these isodose surfaces are intercepted with a plane parallel to the irradiator at 6 cm from the irradiator, data show that the lines resulting from interception of these two surfaces are approximately circumferences.

Analysis of the horizontal distribution of the doses and its gradient shows a good agreement between the experimental and simulated results. This is an indication that the setup of the sources inside the irradiator is correctly defined in this dimension.

In the vertical axis the agreement is not so good and it is evident from the plots that the experimental isodose curves are lowered relative to the equivalent ones obtained by simulation. This deviation is approximately 12 cm. The referred folding and sliding of the card board can justify about 4 cm. The remaining (8 cm approximately) can be attributed to a poor definition of the localization of the sources in the irradiator. It also must be emphasized that the data relating to the irradiation position

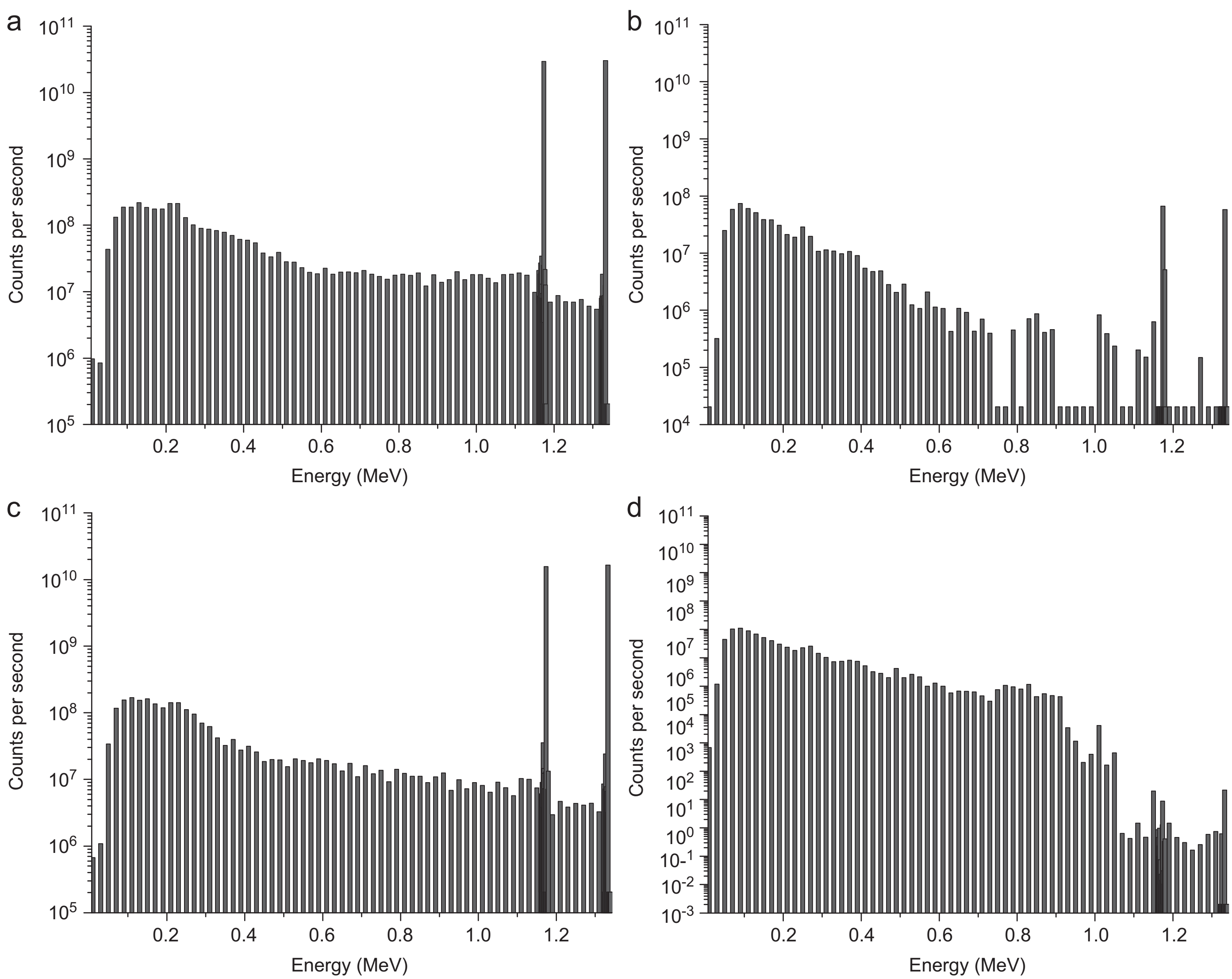

Fig. 6. (a) Photon spectrum at position 1 (Fig. 1) obtained with MCNPX. (b) Photon spectrum at position 2 (Fig. 1) obtained with MCNPX. (c) Photon spectrum at position 3 (Fig. 1) obtained with MCNPX. (d) Photon spectrum at position 5 (Fig. 1) obtained with MCNPX.

(mainly the height to floor) have been transmitted from the supplier and never have been checked.

The shape of the experimental isodose curves between 16 and 24 kGy also seems coherent with a non-symmetric folding, in which the right side of the card was more affected. Nevertheless, it is clear that both plots show a similar behaviour.

A comparison between each pair of equivalent values (experimental and simulation) was made. For this purpose the percentage of deviation of the simulation (MC) results from the experimental (exp) ones ([(MC-exp)/exp] x 100%) has been calculated. These values were grouped in classes. In Fig. 5 the respective frequency histogram is plotted.

As can be noted more than half values (64%) show differences lower than 10%. Higher differences may be due to the reasons mentioned before. The maximum of the distribution is between 0% and 10%, showing a tendency to an overestimation by the simulation.

Table 1
Experimental and simulated values of air-kerma rate.

Position	Exp. (Gy/h)	Irradiator at **its supposed height**		Irradiator 15 **cm below its supposed height**	
		MC (Gy/h)	(Exp./MC)	MC (Gy/h)	(Exp./MC)
1	1628×10^3	1503×10^3	1.08	1510×10^3	1.08
2	3981×10^1	3665×10^1	1.09	3787×10^1	1.05
3	8347×10^2	8635×10^2	0.97	8649×10^2	0.97
4	4214×10^3	4125×10^3	1.02	4110×10^3	1.03
5	3586×10^0	3685×10^0	0.98	3886×10^0	0.92

The results for an irradiator positioned 15 cm below of the initial configuration are also presented.

3.2. Determination of the air kerma inside the empty irradiation room

The gamma flux and the air-kerma rate inside the irradiation room have been measured and calculated in the five locations shown in Fig. 1. Since doubts have arisen about the position of the irradiator, these calculations were also made considering the irradiator 15 cm below its supposed height.

In Fig. 6(a)–(d) photon spectra at positions 1, 2, 3 and 5 are shown.

The spectra corresponding to point 1 and point 3 are very similar, which is due to the position of these points. Photons reaching these frontal positions have a low scattering process in the irradiator (for point 1 is the lower). On the contrary, the photons reaching point 2 are strongly scattered within the irradiator by the ^{60}Co sources itself and by the steel structure that holds the irradiator. The point 5 does not "see" the irradiator and the photons reaching it have at least one interaction outside the irradiator. Its intensity is nearly three orders of magnitude lower than point 1.

The spectra average energies corroborate what has been said before. For points 1, 2, 3 and 5 the following average energies were calculated: 775, 204, 698 and 165 keV, respectively. As expected, the positions where the photons are expected to have less scattering have higher average energies.

The experimental and simulation results are presented in Table 1. The relative uncertainty of the MCNPX results presented, corresponding to one standard deviation, is below 5%. The experimental results have an uncertainty of 0.9% for positions 1 to 4, and 1% for position 5.

The results reveal an excellent agreement but are not conclusive about the real position of the irradiator. Nevertheless,

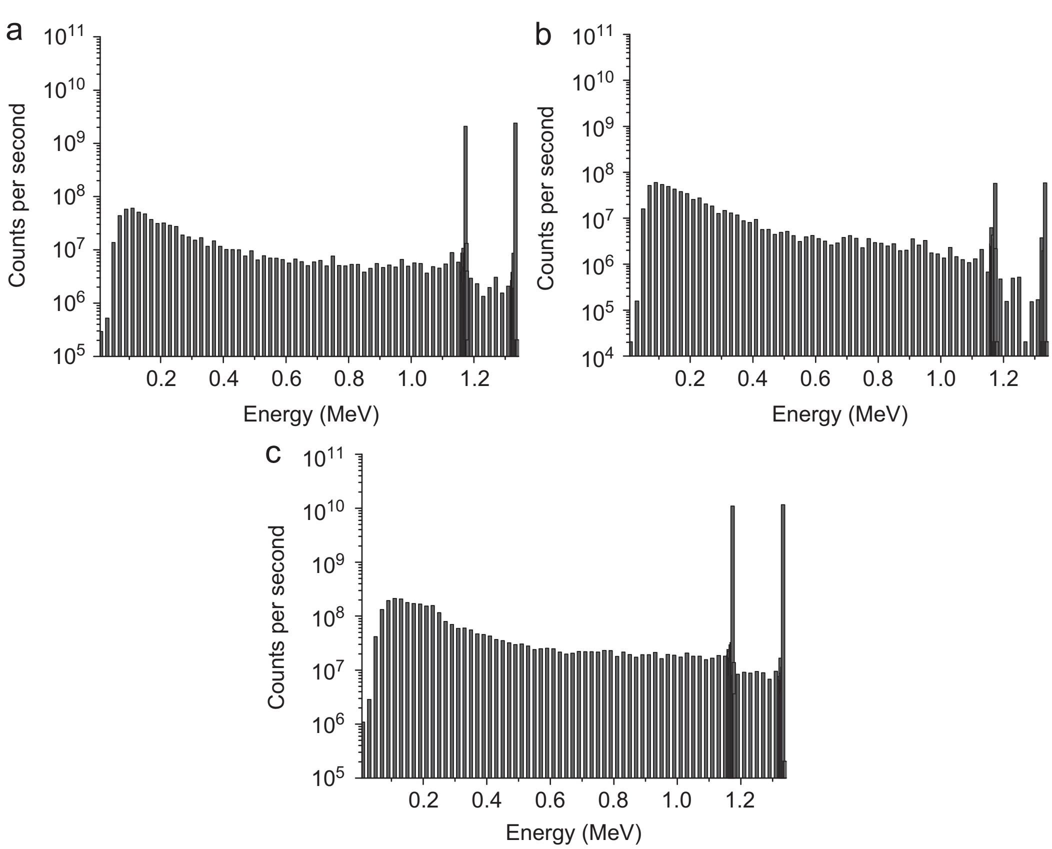

Fig. 7. (a) Photon spectrum at position 10 (Fig. 2) obtained with MCNPX. (b) Photon spectrum at position 11 (Fig. 2) obtained with MCNPX. (c) Photon spectrum at position 12 (Fig. 2) obtained with MCNPX.

Table 2
Absorbed dose rate: experimental and simulation results.

Position	Height (cm)	Gammachrome YR dosimeters (Gy/h)	MC (Gy/h)	Exp./MC
10	173.5	1.15×10^{2}	1.22×10^{2}	0.94
	130	6.48×10^{1}	1.40×10^{2}	0.46
11	173.5	5.04×10^{1}	4.32×10^{1}	1.17
	130	5.40×10^{1}	4.68×10^{1}	1.15
12	173.5	5.40×10^{2}	4.68×10^{2}	1.15
	130	6.48×10^{2}	5.76×10^{2}	1.13

a possible shift in the irradiators position does not have a significant impact on the dose determined inside the irradiation room for the studied localizations.

3.3. Determination of the absorbed dose inside the irradiation room filled with boxes of cork stoppers

The gamma flux and the absorbed dose rate inside the irradiation room have also been measured and calculated in three locations inside the irradiation room with boxes filled with cork stoppers (ρ=0.102 g cm^{-3}). These locations can be seen in Fig. 2.

In Fig. 7(a)–(c) photon spectra at positions 10, 11 and 12 obtained with the MCNPX code are shown.

The proportion between the unscattered ^{60}Co photons and the remaining of the spectrum is quite different in position 11 from what is observed for positions 10 and 12. Consequently, the average energy is 283 keV, lower than the 568 and 603 keV in positions 10 and 12, respectively. The differences between the spectra corroborate the justifications discussed previously.

Comparing positions 10 and 12 with the equivalent 1 and 3 (Fig. 1) a decrease on the average energy of the spectra due to the attenuation of the radiation in the boxes is observed. On the contrary, in position 11 there was an increase in the average energy relative to position 2 (Fig. 1). This effect is due to the radiation scattering and channelling between the 2nd and 3rd rows of the boxes. The consequence is a higher flux of photons with less attenuation reaching position 11 and increasing the average energy.

The experimental absorbed dose and simulation results are presented in Table 2. The relative uncertainty of the MCNPX results presented, corresponding to one standard deviation, is about 1%. The experimental results have a measurement standard deviation below 4%.

The main sources of uncertainties are the reproducibility of the YR dosimeter and the uncertainty associated to the position of the boxes. In fact, the carriers suspended from the monorail conveyor constitute a mechanism with some degree of freedom resulting in some uncertainty in the actual position of the boxes. This uncertainty was not considered in this work but it can influence the transmission of radiation through the boxes and by consequence the calculus of the dose. The results, experimental and calculated ones, are coherent in terms of the higher value which is obtained in position 12. In fact, position 12 is closer to the irradiator than positions 10 and 11. Furthermore, in position 11 the photons emitted by each source are attenuated by the other sources on its side and by the steel structure that holds the irradiator, while in positions 12 and 10 the attenuation is mainly due to the material inside the boxes.

The lower value in position 10 relative to position 12 seems to be mainly due to the higher distance to source and larger material length crossed.

It can be concluded that with the exception of one position, where the agreement is rather poor (position 10, h=130 cm), the remainder experimental results obtained with the individual Gammachrome YR dosimeters are in reasonable agreement with the absorbed doses calculated. The ratio between the experimental and calculated values does not surpass 17%.

4. Conclusions

The Monte Carlo method has been used to validate the irradiator, both for its geometry and for its actual activity. The results seem to indicate that the geometry used for simulation studies have a shift on the vertical dimension relative to the actual geometry of approximately 8 cm. The results also show that this shift may influence the dose value at positions very close to the irradiator but if the distance to the irradiator increases the influence of the shift is reduced or vanishes. Considering all uncertainties associated with the process (including the detected shift of the irradiator) the activity of the irradiator stated by supplier can be used in further works.

In conclusion, the model of the irradiation facility adopted in this study is sufficiently good to predict various operational parameters, such as absorbed doses in the boxes and dose uniformity. The use of such a simulation model can save time, material and human resources.

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