NUCL SCI TECH (2017) 28:133
DOI 10.1007/s41365-017-0289-5

Combining Monte Carlo simulations and dosimetry measurements for process control in the Tunisian Cobalt-60 irradiator after three half lives of the source

Leila Ounalli[1,2] · Maroua Bhar[3] · Arbi Mejri[1] · Kais Manai[4,5] · Ammar Bouabidi[1,4] · Shayma Mohamed Abdallah[4] · Nafaa Reguigui[1]

Received: 8 December 2016 / Revised: 7 April 2017 / Accepted: 12 April 2017 / Published online: 16 August 2017

Abstract To check the dose uniformity and to determine the efficiency of medical devices sterilization by gamma irradiation after three half lives of the source, calculations of the absorbed dose were carried out. Monte Carlo simulations and dosimetry measurements, were established to study the radiation processing quality control. An isodose chart was created by GEANT4 Monte Carlo code to evaluate the absorbed dose rate uniformity inside the irradiation room from the year of the installation until the year of the source reload. The dose uniformity ratio (DUR) is deduced from maximum and minimum experimental doses in medical devices after three half lives of the source.

Keywords Cobalt-60 · Monte Carlo calculation · Sterilization · Medical devices · Dose rate · Uniformity · PMMA dosimeter · Dose mapping

✉ Leila Ounalli
leila.ounalli@cnstn.rnrt.tn; leila.ounalli@gmail.com

1 Tunisian Center for Nuclear Sciences and Technology, Technopark Sidi Thabet, 2020 Ariana, Tunisia

2 Laboratory on Energy and Matter for Nuclear Sciences Development, Technopark Sidi Thabet, 2020 Ariana, Tunisia

3 Tunisian Higher Institute of Medical Technologies, 9 Rue Zouhair Essafi 1006 TUNIS, 1006 Tunis, Tunisia

4 Faculty of Sciences of Tunis, Technopark Sidi Thabet, 2020 Ariana, Tunisia

5 College of Science and Arts, University of Bisha, Bisha, Kingdom of Saudi Arabia

1 Introduction

Hundred of industrial gamma irradiation facilities (especially ^{60}Co source) are in operation worldwide, as listed in the IAEA database [1].

Tunisian legislation were enacted in April and May 2002 to regulate respectively, sterilization of medical devices with single use (syringe, surgical gowns, suture, etc.) and the radiation processing of fresh foods (fruits, vegetables, salads and meat products, potato, garlic, onions, etc.) as well as dry foods (dehydrated or dried spices, dried fruits, dried vegetables, etc.).

Over the years, the decrease in the source activity and thus the dose rate affects the irradiation time. Consequently, it is necessary to compensate the dose rate decrease by incrementally increasing the irradiation time, which has a significant impact on the cost and scheduling of the radiation processing. This causes doubt on the homogeneity of the dose distribution.

The safe management and the dosimetry quality control were first conducted after one half-life of the source (commissioning at 1999) and were studied by different ways [2–5].

Since the Tunisian ^{60}Co source is near the end of its useful life, the present study is focused on sterilization of single use medical devices. The objective was to evaluate the efficiency of sterilization of medical devices by gamma irradiation at the third period of the source half life.

The procedures established at the ^{60}Co source process control for the irradiation of medical devices had been consistent with the relevant good radiation processing (GRP) requirements. In addition, IAEA guidance [6] and ISO 11137 standards under parts: 1 [7], 2 [8], and 3 [9] related to radiation sterilization for healthcare products are provided.

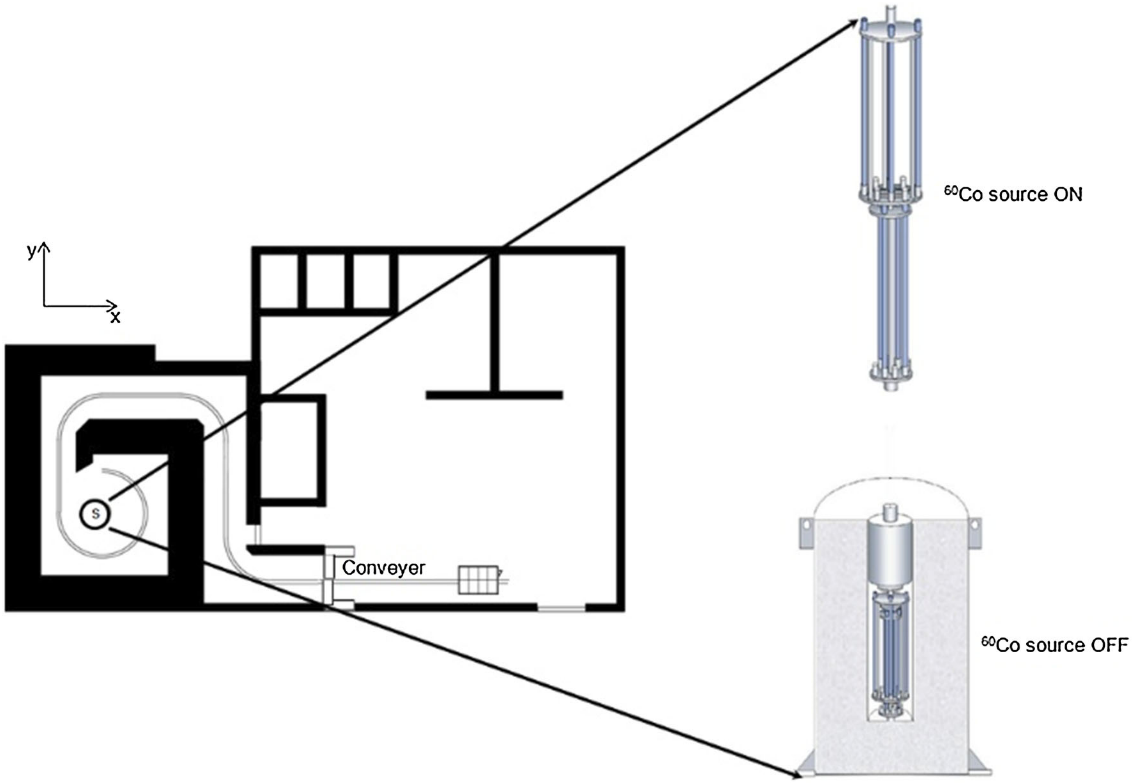


Fig. 1 A geometric view of the Cobalt-60 irradiator with the source pencils in off and on modes

At the third period of the ^{60}Co source half-life, very long irradiation time is necessary to deposit the desired dose in the 'high needed irradiation time' product (e.g. spices, medical devices with single use). Indeed, it becomes necessary to control the quality of the processing in terms of absorbed dose rate and dose rate uniformity.

The experimental measurements are expensive and need a lot of time. Thus, it was useful to resort to GEANT4 in dose rate calculations. As already demonstrated by Kadri et al. [10], the excellent agreement seen between the dose rates calculated by GEANT4 and the measured values allow us to apply such code in order to determine the ^{60}Co irradiation facility efficiency after 16 years of use.

In order to understand the spatial variation of the dose rate distributions during a radiation sterilization process, the dose distribution around the ^{60}Co source was estimated. For this purpose, a comprehensive dose rate mapping study was carried out using both simulations and experimental measurements. We were able to determine the dose rate uniformity ratio over the years.

To our knowledge, the measurement of the dose distribution delivered by the ^{60}Co industrial irradiator and the efficiency of medical devices irradiation at the end of source life had never been done before.

2 Materials and methods

2.1 Description of the ^{60}Co irradiator

The Pilot-scale gamma irradiation facility is utilizing ^{60}Co pencils. The initial activity that was loaded into the facility was 3.626 PBq on April 09, 1999 (date of commissioning). The C-188 MDS Nordion ^{60}Co gamma irradiator is a 'category II' facility. The source rack is a panoramic dry source storage for continuous operations (see Fig. 1). It contains eight ^{60}Co pencils of 7.2 and 410 mm of diameter and height, respectively. The sources, doubly encapsulated in a welded stainless steel cage, are cylindrically arranged on two pitch circles of 102 and 56 mm diameters, respectively.

The cylinders holding the source pencils were designed with 20 housing for future loading. The size of the irradiation chamber is 6 m × 6 m × 3 m. It is surrounded by walls made of 1.7 m high-density concrete. When sources are not in use, they are stored in a lead cylindrical shield container with a radius of 0.332 m and height of 1.166 m. The irradiation process can be monitored from the control room adjacent to the irradiation chamber. More description of the facility is shown in Ref. [2].

2.2 Dosimeters

Red Perspex dosimeters 'type 4034 (Harwell, UK)' are known for their sensitivity to the absorbed dose range (5–50 kGy) linear response. They are suitable for radiation processing applications, especially in sterilization of soft materials such as single use medical devices [11, 12].

The active substance of dosimeters is composed of a dye dispersed in the poly-methylmethacrylate (PMMA) and sealed in polyethylene–aluminum sachets. The sheets are cut into plaques of 30 mm × 11 mm of size and 3 mm of thickness (±0.55). Gamma radiation leads to the ionization of PMMA and the added dye. The radicals of ionized polymer react with the dyed molecules to produce an optical absorption in the visible spectrum.

The perusal of dosimeters was realized 24 h after irradiation using the Aerial Optical Dosimetry Equipment at 640 nm wavelength [13].

The irradiation has been performed in air at the ^{60}Co gamma irradiation facility at the dose rate: 100 Gy/min [2]. The dose rate was established with the alanine/EPR dosimetry system in terms of absorbed dose traceable to the National Physical Laboratory, UK [12]. Before the experiment, the dose rate was verified by a standard Fricke dosimeter.

2.2.1 Uncertainty measurements

Uncertainties of measurements at 1σ (95% confidence interval) were evaluated following ISO/ASTM Guides procedures [12–14] and were found to be ±4.5% for the calibrated dosimeter.

The methodology for evaluating components of the uncertainty are shown as follows:

– *n* Red Perpex dosimeters were irradiated with the same dose in the same conditions of irradiation.
– The values of the corresponding absorbance were read from the Arial Spectrophotometer for each dosimeter.
– The values of the thickness were read from the gauge of spectrophotometer.
– The average dose was calculated for all the *n* dosimeters.
– Uncertainties on the measures of the absorbed dose were determined.

The typical uncertainty on the dose absorbed by a Red Perpex dosimeter is a quadratic combination of various sources of uncertainties:

$$U^2(D) = U^2(C) + U^2(R) + U^2(ref)$$

With:

$U^2(C)$: Uncertainty on the establishment of the curve of calibration (C),
$U^2(R)$: Uncertainty on the response (R) of the dosimeter,
$U^2(ref)$: Uncertainty established by the reference (ref) laboratory (2.5 %).

The balance of the global compound uncertainties is given by the Table 1.

2.3 Simulated setup in the GEANT4 Monte Carlo code

GEANT4 (GEometry ANd Tracking, version 4) [15, 16] is used in the present study.

For the dose rate calculation, the geometry of the ^{60}Co facility is constructed using the DetectorConstruction class of GEANT4. For this purpose, the standard geometry bodies included in GEANT4 were used while respecting the dimensions and the real compositions of the ^{60}Co irradiator with the source pencils in on mode as described in the Sect. 2.1.

In this work, we are interested in the weak decay of the ^{60}Co source and electromagnetic interactions of generated gammas (γ1 and γ2 of the ^{60}Co) with matter (air and dosimeters). Particles, processes, and the default cut value

Table 1 Balance sheet of the uncertainties

Components of the uncertainty		Uncertainty for the wavelength 410 nm (%)	Uncertainty for the wavelength 600 nm (%)
Uncertainty on the response of the dosimeter	Uncertainty on the measure of the optical absorbance	1,054	1,057
	Uncertainty on the measure of the thickness	3,04	
Uncertainty on the curve of calibration		1,79	2,03
Global compound typical uncertainty		4,44	4,54

(1 mm) are implemented using the G4Physicslist class. The generation of gamma photons with their characteristics is modeled using the G4PrimaryGenerationAction class.

PMMA dosimeters were assumed to be spheres in order to obtain the same surface exposed to the radiation. Based on statistical studies, the most appropriate radius of these spheres is 4 cm [17]. This radius leads to a low statistical error (less than 5%).

The mass of the dosimeter is defined as $m_{\mathrm{d}} = d \times V = 1.19 \times (4\pi r^3/3)$

With:

d: Material density of the dosimeter (g/cm^3),
V: Dosimeter volume (cm^3),
r: Sphere radius (cm).

After defining the parameters of particles generation, the absorbed dose rates were calculated by transforming the deposited energy in the dosimeter during a series of events, N, as follows:

$$\dot{D}(\mathrm{Gy/min}) = E_{\mathrm{d}}(\mathrm{MeV}) \times \frac{2 \times A(\mathrm{Bq}) \times C \times t}{N \times m_{\mathrm{d}}(\mathrm{g})}$$

With:

E_{d}: Total energy deposited in a dosimeter (MeV),
C: Conversion factor (J/MeV), equal to 1.602×10^{-10},
A: Activity in (Bq),
N: Number of generated events, equal to 10^7,
2: Factor to take into account two emitted photons by the ^{60}Co source,
t: The irradiation time, equal to 60 min.

3 Results and discussion

3.1 Experimental results

In this section, we present the absorbed dose during a routine processing of single-use medical products from 2009 to 2015.

3.1.1 Process control in the product over the years

Besides the transversal variation of the dose, there is also the dose variation in the lateral direction. Both types of the dose variation contribute to the non-uniformity of the dose delivered to the product. However, one must keep in mind that dose variation in the irradiated product is unavoidable. The concept of dose uniformity ratio (DUR), defined as the ratio of the maximum to the minimum of dose in the irradiated product [17], is used in the present work.

Dosimeters were placed at the minimum and maximum dose positions during routine irradiation of a process load (Fig. 2). The maximum and the minimum doses are determined after a cartography of the irradiated product.

In this part of study, the Red Perpex dosimeters described in Sect. 2.2 were used. The dosimeters associated with the device are analyzed after irradiation of the product is complete, to confirm that the required dose has been delivered.

The dose distribution measurements were carried out with the same single-use medical product with a density of 0.114 g/cm^3. The size and the mass of the product boxes are 58 × 39 × 31 cm and 7 kg, respectively. Sixteen boxes with dimensions of 80 cm × 58 cm × 62 cm were used for the processing batch. Four product boxes were used for irradiation (see Fig. 1).

In order to reach its desired dose and to improve dose distribution, the irradiated product has to receive dose increments. Similar conditions of irradiation were respected, except the irradiation time and the dose rate, which were adjusted to compensate the source decay.

The regions of minimum and maximum absorbed doses within the product were determined, and the DUR was deduced.

The results of irradiation of several batches of product, done during the third source half-life period (2009–2015), are shown in Fig. 3. Consistency of dose received by irradiated products per irradiation is demonstrated.

3.1.2 Dose rate and processing irradiation time compensation

Currently, the irradiation time of the product is much longer in comparison with the first years. It took a few days in the beginning of source installation and now takes weeks for the sterilization of single use medical products.

Figure 4 shows evidence of satisfactory processing. Even with the decrease in source activity, compensation with the increase in the irradiation time and the decrease in dose rate is a proper manner of processing.

Process interruption is sometimes encountered. Some interruptions may be planned; for example, double-side irradiations may be used to improve the dose distribution. Other interruptions may be the result of unplanned irradiator shutdowns [18].

3.1.3 Dose uniformity ratio

The dose variation in the lateral direction of the product is presented in the DUR value, which is a method of describing the non-uniformity of the dose delivered to the product. Figure 5 recapitulates the deduced DUR as the

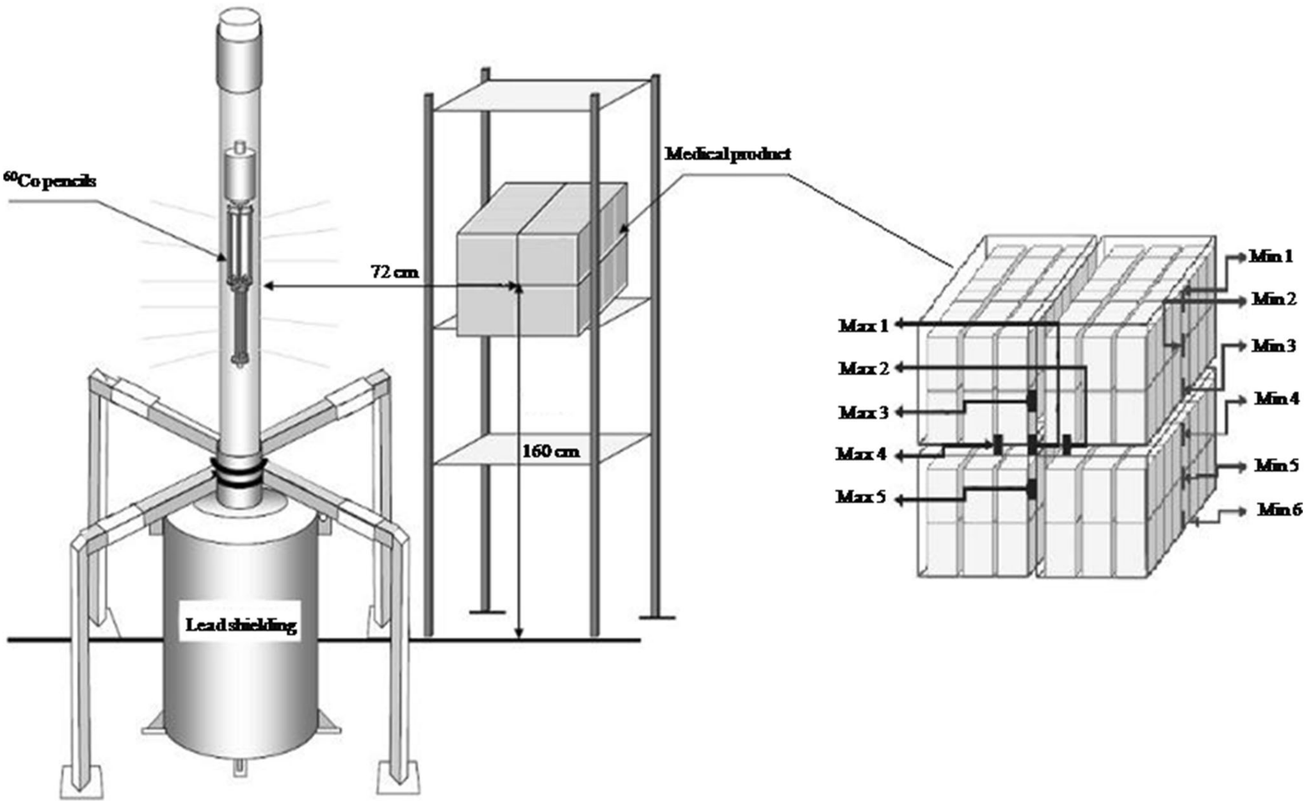
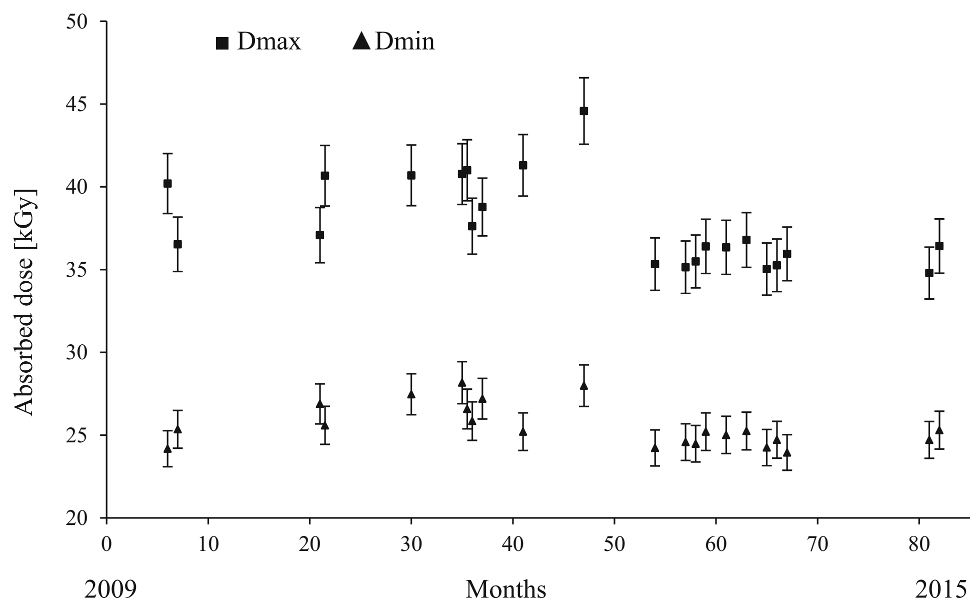


Fig. 2 A detailed geometry of the experimental setup with the irradiated boxes (*left*) and the placement of PMMA dosimeters (*right*). D_{max} and D_{min} are the mean values of maximum and minimum doses, respectively

Fig. 3 Minimum and maximum doses received by single-use medical product during the third source half-life period



ratio of the measured maximum and minimum doses delivered to the product over the third source half-life period.

Keep in mind that the dose limit ratio is between 1.5 and 3 for many applications [19] and sometimes even larger depending on the product and the process. We assume that

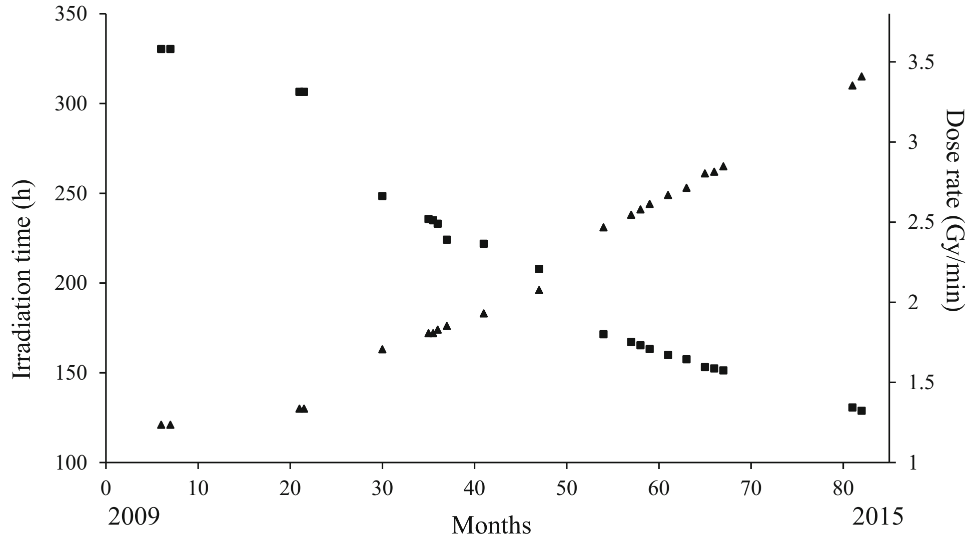


Fig. 4 The irradiation time (*triangle*) and the dose rate (*square*) recorded during the process control of single-use medical product during the third source half-life

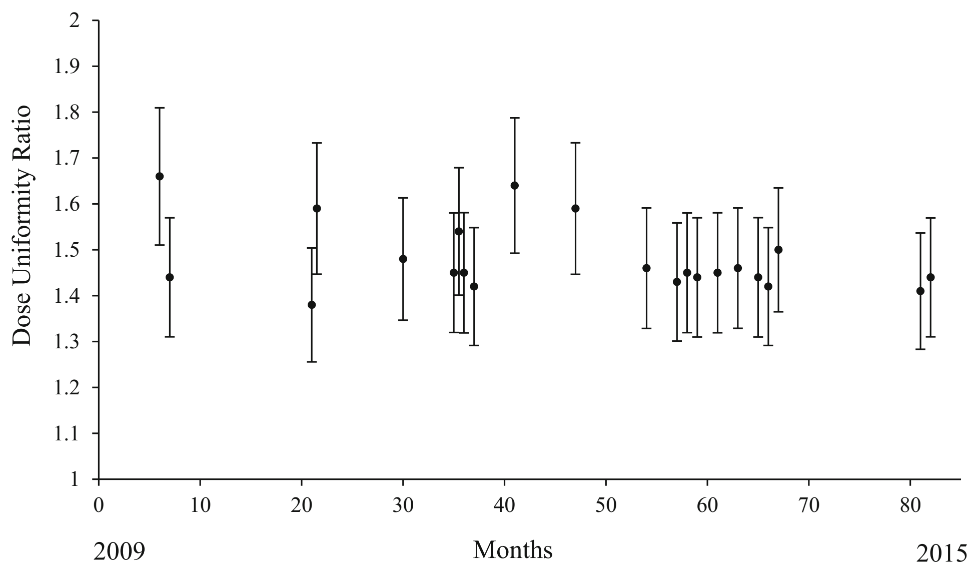


Fig. 5 Dose uniformity ratio during the third source half-life period

dose variation in the irradiated product is small and the dose delivered to the product is uniform.

3.2 Monte Carlo calculations

- In the first part, validation of the GEANT4 setup was carried out by comparing our results of absorbed dose rates to those obtained previously by Ref. [11]. A comparison between dose rates at the first source half-life (2004) and at the third source half-life (2015) was also studied.
- The second part is dedicated to the absorbed dose rate calculations resulting from the gamma energy deposited in PMMA dosimeters (simulated dosimeters put equidistantly around the source). This study concerns the years between 1999 and 2018: commissioning and planned pencils reloading date.
- The third part is focused on the study of the dose distribution uniformity during the operation years.

3.2.1 Validation of the GEANT4 setup

Previously, Kadri [17] measured the dose rates experimentally and compared them with GEANT4 calculations in seven critical points. PMMA's dosimeters were placed in the irradiation room at 157 cm of height. Seven points are sorted from the most distant to the closest one to the source.

In the present work, dose rate calculations were carried out using GEANT4. The hardware platform used to run the GEANT4 version 9.2 code is a Linux (Scientific Linux CERN 5) Personal Workstation with 8 GB RAM and a

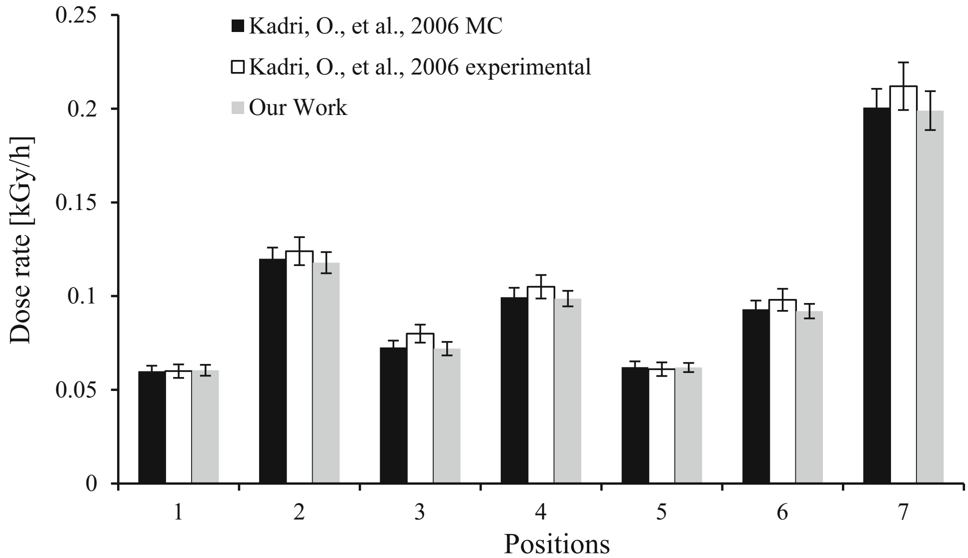


Fig. 6 A comparison of present work results with a past reference

3.4 GHz CPU. Similar results (less than a 3% difference) were obtained compared with those determined by Ref. [17], which used the version 6.1 to calculate dose rates at different dosimeters' locations.

As illustrated in Fig. 6, the absorbed dose rate distribution is well preserved. The closest (position 7) and the farthest (position 1) points from the source have, respectively, the highest and the lowest absorbed dose rates, as expected. Points 2, 4, and 6 are equidistant with regard to the source, which explain their approximately equal dose rates. Points 3 and 5 are symmetric with respect to the point 4. However, point 3 is closer to the irradiation room corner, which explains its slight elevation compared to point 5.

In the next part, we calculate the dose rates at the seven points in the year 2015, which corresponds to the third source half-life.

The total activity of the source in 2015 is about 430 ± 0.18 TBq. It is lower than the activity of a single pencil in the year of the installation.

At the third half-life (2015) of the ^{60}Co source, dose rates are around one-third to one-fourth compared to the values obtained during the first half-life (2004), as shown in Fig. 7, which is explained by the source decay.

One take in mind that Geant4 Monte Carlo simulations have some limitations: For example, simulation model cannot consider any small geometric changes of the irradiator setup in its lifespan. In addition, the time component

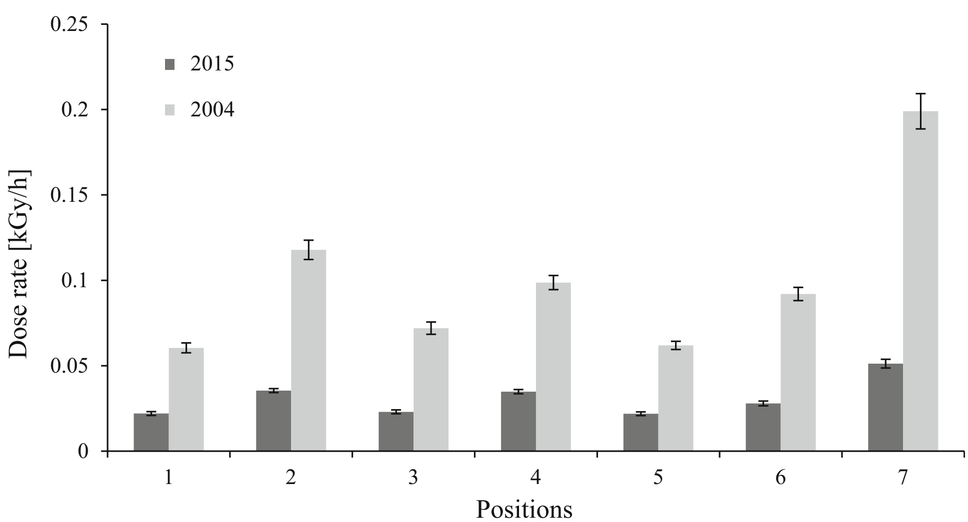


Fig. 7 The absorbed dose rate values in seven critical points for the years 2004 and 2015

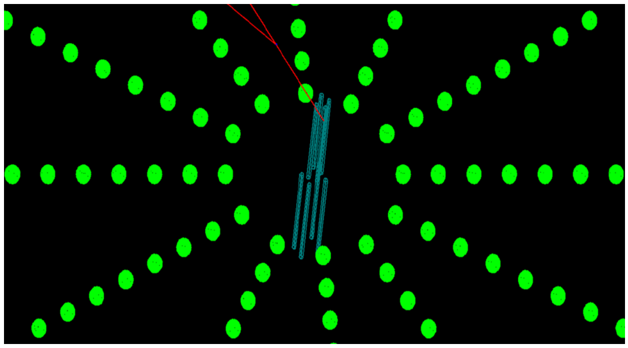


Fig. 8 (Color online) Location of dosimeters on the ten circular levels

is not involved in the dose rate calculation and also the increase of temperature in setup is not taken into account.

3.2.2 *Study of the absorbed dose rate distribution over the years*

The present study is focused on the dose rate distribution uniformity inside the irradiation room from the year of commissioning (April 1999) until the expected year of pencils reloading (April 2018). This study is very important for the transversal isotropy verification of gamma ray emission.

To verify that the angular distribution isotropy is ensured in all directions of the irradiation room, a spherical PMMA-filled scoring dosimeter geometry is implemented for dose rate calculations. G4PVPlacement is used to place the 120 dosimeters around the source on 10 circular beam levels with radii extending from 40 to 200 cm at the same height of 157 cm (midplane of irradiation chamber) [2]. In each level, the angle between two consecutive dosimeters is 30° (Fig. 8).

A comparison between the mapping of the calculated absorbed dose for years 1999 and 2015 is illustrated in Fig. 9. The dose rate distribution keeps the circular behavior, and the gamma isotropy is insured at the conveyer level.

The excellent transversal isotropy of the gamma ray emission in the year 1999 remains similar after 16 years of the source use. For both years (1999 and 2015), the deposited energy at the level of conveyer keeps approximately the same value around the ^{60}Co source, which explains the good dose distribution inside the irradiation room. The contribution of photon scattering by the wall around the source was demonstrated lower than statistical errors [3]. At the third source half-life, the anisotropy of the gamma ray emission is preserved far away from the conveyer level.

3.2.3 *The dose distribution uniformity over the years at the level of the conveyer*

Since the year of the installation (1999) until the year of pencils reloading (2018), the dose rate distribution showed a clear decrease. For this purpose, the value of the level dose rate uniformity (at the conveyer level) is deduced.

The level dose rate uniformity is defined as the ratio between the maximum and the minimum dose rates taken at the same distance from the source $(D_{max}/D_{min})_{conveyer\ level}$.

As shown in Fig. 10, the level dose rate uniformity is close to the unity till the end of the source life. Replenishment of source pencils at 2018 to compensate the lost activity could preserve the level uniformity close to the unity.

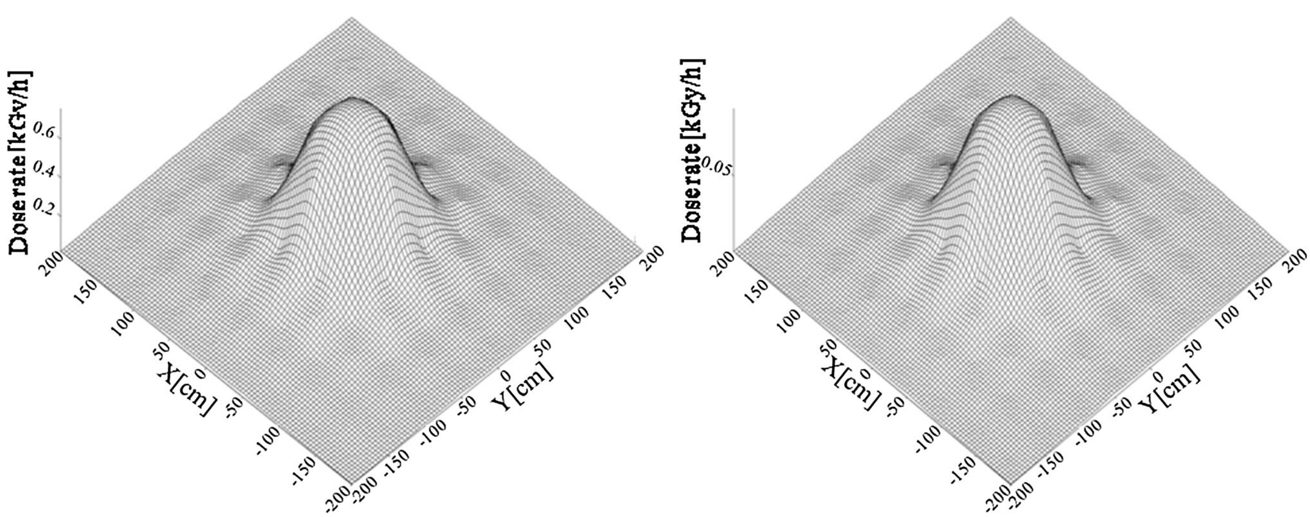


Fig. 9 The mapping of dose rates distributions in the midplane [(*left*) at the year of installation 1999 and (*right*) at the year 2015]

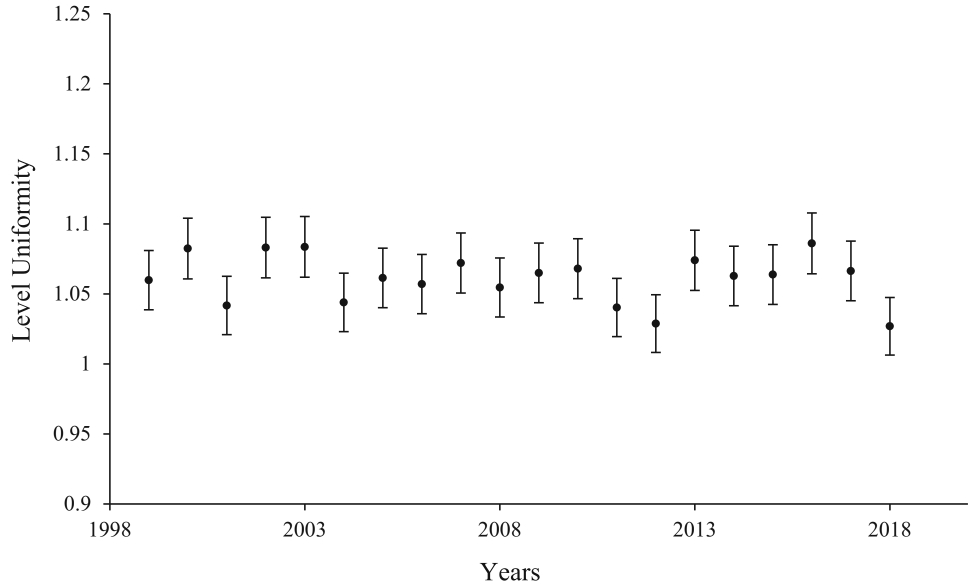


Fig. 10 Evolution of the level uniformity over the years (at the level of the conveyer)

4 Conclusion

The application of GEANT4 for dose mapping in the ^{60}Co irradiator has been found very promising because of its accuracy and fast simulation, and because it is a cheaper way to validate measurements and optimize dosimetry quality control.

Good agreement was obtained over the period starting from the irradiator commissioning in 1999 until the third source half-life, which confirmed the stability of the dosimetry measurements and the Monte Carlo modeling and reconfirmed the half-life of ^{60}Co.

However, the decrease in the source activity can be compensated by the increase in the irradiation time. In practice, this is not possible for certain cases, e.g., processing to preserve fresh food in terms of microbiological safety becomes not feasible, and the range of irradiated products is limited to only soft materials.

To add perspective, the study of the adequate arrangement and pencils activities are underway to compensate the decrease in the source activity and maintain an excellent isodose distribution inside the irradiation room.

Acknowledgements The authors would like to acknowledge all the staff of the Ionizing Radiation Unit for their availability and support of this work.

References

1. IAEA-DGPF/CD, Directory of Gamma Processing Facilities in Member States, A technical document issued by the International Atomic Energy Agency (2004). http://www-pub.iaea.org/MTCD/publications/PDF/dgpf-cd/PDF/Contents.pdf. Accessed 14 Feb 2016
2. K. Farah, T. Jerbi, F. Kuntz et al., Dose measurements for characterization of semi-industrial ^{60}Co gamma irradiation facility. Radiat. Meas. **41**, 201–208 (2006). doi:10.1016/j.radmeas.2005.03.003
3. F. Gharbi, O. Kadri, K. Farah et al., Validation of GEANT4 code of CERN a predictive tool of dose rate measurement in the Tunisian gamma irradiation facility. Radiat. Phys. Chem. **74**, 102–110 (2005). doi:10.1016/j.radphyschem.2005.02.006
4. O. Kadri, F. Gharbi, K. Farah, Monte Carlo improvement of dose uniformity in gamma irradiation processing using the GEANT4 code. Nucl. Instrum. Methods B **239**, 391–398 (2005). doi:10.1016/j.nimb.2005.05.052
5. O. Kadri, F. Gharbi, A. Trabelsi, Monte Carlo optimization of some parameters in gamma irradiation processing. Nucl. Instrum. Methods B **245**, 459–463 (2006). doi:10.1016/j.nimb.2005.11.142
6. IAEA-TECDOC-539, Guidelines for industrial radiation sterilization of disposable medical product. A technical document issued by the international Atomic Energy Agency (1990). http://www-pub.iaea.org/MTCD/publications/PDF/te_539_web.pdf. Accessed 14 Feb 2016
7. ISO 11137-1, Sterilization of health care products—radiation—part 1: requirements for development, validation and routine control of a sterilization process for medical devices (2006)
8. ISO 11137-2, Sterilization of health care products—radiation—part 2: establishing the sterilization dose (2013)
9. ISO 11137-3, Sterilization of health care products—radiation—part 3: guidance on dosimetric aspects (2006)
10. O. Kadri, F. Gharbi, K. Farah et al., Application of GEANT4 code in gamma irradiation processing. Int. J. Theor. Phys. **14**, 1–15 (2009)
11. W.L. McLaughlin, M.F. Desrosiers, Dosimetry systems for radiation processing. Radiat. Phys. Chem. **46**, 1163–1174 (1995)
12. ISO/ASTM 51276, Standard practice for use polymethyl methacrylate dosimetry system. American Society for Testing and Materials, Philadelphia (2002)
13. F. Kuntz, R. Fung, A. Strasser, A dedicated tool for the quality assurance in the field of radiation processing. Proceeding of the

11th International Meeting on Radiation Processing, Melbourne (Australia) (1999)

14. ISO/ASTM 51707, Standard guide for estimating uncertainties in dosimetry for radiation processing. ftp://185.72.26.245/Astm/2/01/Section%2012/ASTM1202/PDF/ISOASTM51707.pdf
15. S. Agostinelli, J. Allison, K. Amako et al., GEANT4—a simulation toolkit. Nucl. Instrum. Method A **506**(3), 250–303 (2003). doi:10.1016/S0168-9002(03)01368-8
16. J. Allison, K. Amako, J. Apostolakis et al., GEANT4 developments and applications. IEEE Trans. Nucl. Sci. **53**(1), 270–278 (2006). doi:10.1109/TNS.2006.869826
17. O. Kadri, F. Gharbi, K. Farah et al., Monte Carlo studies of the Tunisian gamma irradiation facility using GEANT4 code. Appl. Radiat. Isotopes **64**, 170–177 (2006). doi:10.1016/j.apradiso.2005.07.009
18. E.G. Cabal, L.G. Lanuza, H.M. Solomon, Process control and dosimetry in a multipurpose irradiation facility. Radiat. Phys. Chem. **55**, 781–784 (1999)
19. A. Mejri, K. Farah, F. Hosni et al., An empirical model for predicting Harwell dose variation during gamma process interruption using experimental design. MAPAN-J. Metrol. Soc. India **30**(2), 85–90 (2015). doi:10.1007/s12647-014-0129-6