Available online at www.sciencedirect.com
ScienceDirect
Applied Radiation and Isotopes 65 (2007) 701–707
Applied Radiation and Isotopes
www.elsevier.com/locate/apradiso

Evaluation using GEANT4 of the transit dose in the Tunisian gamma irradiator for insect sterilization

K. Mannai[a], B. Askri[a], A. Loussaief[a], A. Trabelsi[a,b,*]

[a]Unité de Recherche de Physique Nucléaire et des Hautes énergies, Département de Physique, Faculté des Sciences de Tunis, El-Manar 2092, Tunisia
[b]Centre National des Sciences et Technologies Nucléaires, Technopole de Sidi-Thabet 2020, Tunisia

Received 3 May 2006; received in revised form 1 October 2006; accepted 9 January 2007

Abstract

A simulation study of the Tunisian Gamma Irradiation Facility for sterile insects release programs has been realized using the GEANT4 Monte Carlo code of CERN. The dose was calculated and measured for high and low dose values inside the irradiation cell. The calculated high dose was in good agreement with measurements. However, a discrepancy between calculated and measured values occurs at dose levels commonly used for sterilization of insects. We argue that this discrepancy is due to the transit dose absorbed during displacement of targets from their initial position towards their irradiation position and displacement of radiation source pencils from storage towards their irradiation position. The discrepancy is corrected by taking into account the transit dose.

Keywords: Monte Carlo; GEANT4; Irradiation facility; Transit dose

1. Introduction

Irradiation by ^{60}Co sources is a method widely used in research, industry and agriculture. Specific γ-irradiation facilities are used to sterilize live insects for pest management programs. As part of the operation procedure for such facilities, a detailed dose mapping of the irradiation cell should be realized to establish plant operational parameters, such as dose uniformity, source utilization efficiency, and maximum and minimum dose positions. These parameters may be obtained through dosimetric measurements as well as by computer calculations. Experimental dosimetry procedures require calibration dosimeters which results in high costs and long death time for the facility. On the other hand computer calculations are applicable for both existing facilities and to a design work. For this purpose, Monte Carlo methods are used to achieve reliable radiation transport calculations for various investigations (Oliviera et al., 2002; Soharabpour et al., 2002; Gharbi et al., 2005). In the present work we study the absorbed dose during displacement of targets from their initial position towards their irradiation position and displacement of radiation source pencils from storage towards their irradiation position. We refer to this dose, henceforth, as the transit dose. This dose is often neglected when dealing with industrial irradiators. In the case of irradiators for insect sterilization which have a relatively small geometry and operate at low dose (Follett, 2004; Hallman, 1999), the transit dose could be significant especially for high dose rates (HDR), especially in nuclear medicine and portal image (Wojcicka et al., 1999; Calcina et al., 2005; Bogaerts et al., 2000). The transit dose depends on the prescribed dose, number of treatment fractions, speed and activity of the source and velocity of the target. In the case of HDR, the total absorbed dose contains a dynamic component during the movement of the source; as a consequence the absorbed dose is higher than the prescribed one and often this difference is not included in the operation planning. The evaluation of the transit dose would be an additional tool for quality control of the irradiation processing. The present work was carried out

*Corresponding author. Centre National des Sciences et Technologies Nucléaires, Technopole de Sidi-Thabet 2020, Tunisia.
Fax: +216 71 537 555.
E-mail address: adel.trabelsi@cern.ch (A. Trabelsi).

0969-8043/$ - see front matter
doi:10.1016/j.apradiso.2007.01.011

using the Monte Carlo GEANT4 code of CERN to investigate the importance of the transit dose contribution on the dose distribution in a given irradiation cell.

2. Experimental procedure

2.1. Irradiation plant

The Tunisian Gamma Irradiation Facility is designed for irradiation of insects and uses ^{60}Co as a source of gamma-rays. The gross weight of the irradiator is 8300 kg. Main dimensions are: length = 238 cm, width = 96 cm and height = 235 cm. The sample door is located at 109 cm from the ground (Fig. 1). The irradiator is placed in a 3.5 m × 4.5 m room.

The source is composed of 24 cylindrical pencils (radii 0.7 cm, height 23.5 cm) placed on a circle of radius 10.85 cm. These pencils have various activities (see Table 1) and their absolute orientation inside the irradiator is not known. The source cage can hold up to 36 pencils of ^{60}Co. Fig. 2 shows a transversal section of the source cage and its shielding. The loaded ^{60}Co activity is (669± 10%) TBq. The total activity (April 2006) is (390± 10%) TBq. Pencils are stored in a cylindrical container shielded with lead protecting the personnel and the environment against gamma radiation (radii = 12.5–85 cm, height = 25 cm). The source cage is moved up and down by a pneumatic drive mechanism.

An aluminum cylindrical canister (radii 6.5 cm, height 24 cm) is used to hold insects (3.18 kg) to be irradiated.

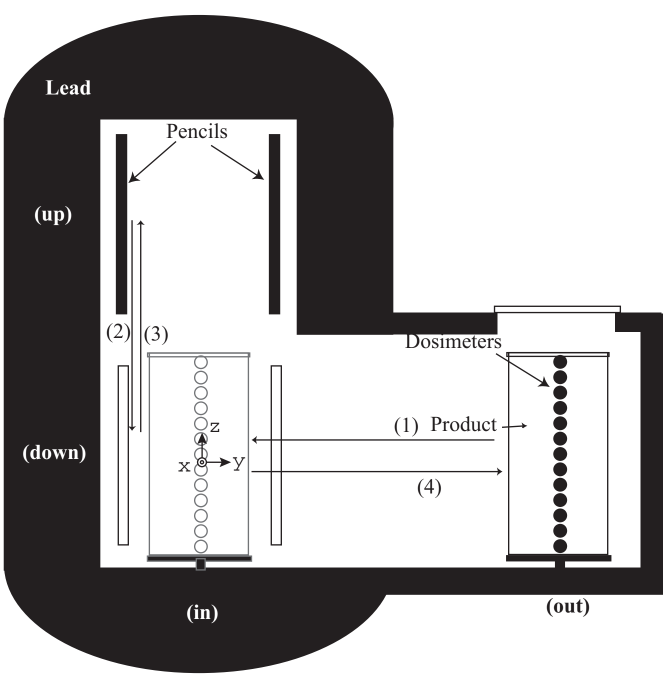

Fig. 1. (1) Displacement of the target before the irradiation from position "*out*" towards position "*in*", (2) descent of the pencils before the irradiation from the storage position towards irradiation position, (3) rise of the pencils after irradiation, (4) displacement of the target after irradiation.

Table 1
Activities of the pencil sources

Pencil number	Activity (TBq)
7	25.70
1;5;13;15;17;21	25.87
9;19	26.04
3	26.20
11	26.37
23	26.50
24	27.17
12;16	27.30
4;8;20	27.47
6;14	31.63
10	31.80
2	32.26
18	32.76
22	33.06

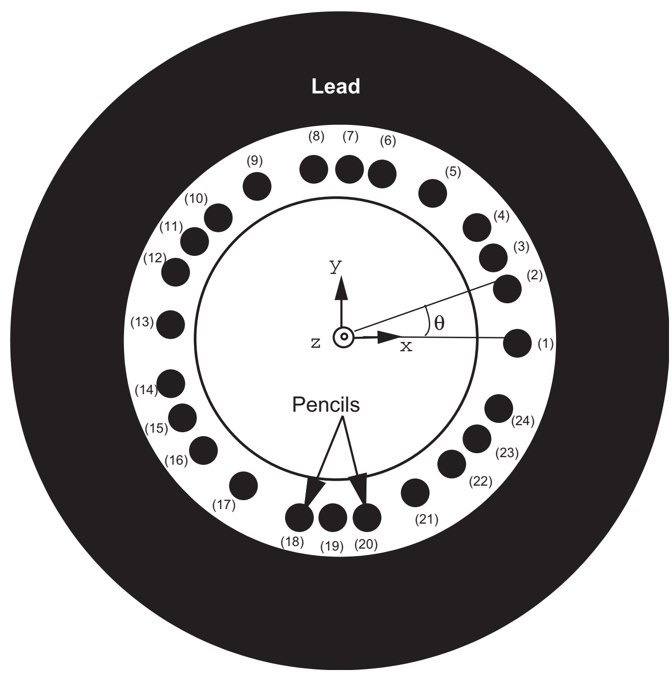

Fig. 2. Transverse schematic view of the irradiator.

Before moving the drawer to the loading/unloading position the source cage is lifted automatically to "up" position. The drawer is moved horizontally by a second pneumatic drive mechanism.

In irradiation position "down" the vertical axis of the chamber of the drawer coincides with the axis of the source cage. The irradiation time (according to the requested dose) should be calculated prior to operation. The irradiation treatment is carried out automatically under the control of a digital timer with an accuracy of 0.1 s.

2.2. Dosimeters

The dose measurements were performed using Red Perspex and Gammachrome PMMA dosimeters in order to validate the Monte Carlo calculations. The Red Perspex and Gammachrome are polymethyl methacrylate (PMMA) routine dosimeters with a standard uncertainty of 3% (6%, at a 95% confidence level) in the range of 5–50 and 0.1–3 kGy, respectively (ISO/ASTM 51276). Measurement of the low level transit dose is carried out using a GafChromics dosimeter (HD810, ISP corp-USA) which has an applicable dose range of some Gy to some kGy with a precision of better than 6% at a 95% confidence level. The determination of absorbed dose was realized indirectly through spectrophotometric evaluation (Spectronic Genesys 5 *UV–VIS* spectrophotometer + Kafer KMF30 thickness gauge + Aer'ODE software (Aer'ODE v 2.1.1) of the specific absorbance. Dosimeters are calibrated against Alanine/EPR at the Laboratory of Dosimetry of AERIAL. The absorbed dose is given relative to that. Dose measurements have been carried out using three PMMA dosimeters for each measurement in order to reduce errors.

2.3. Measurement of transit dose

To measure the transit dose, we placed three GafChromics dosimeters (square film of dimension 1 cm × 1 cm) along the vertical axis in the positions ($z = 11.5$, 0 and -11.5 cm) during a significant number of cycles of rise and descent of the source. In the present work 20 cycles of rise and descent of the source are performed setting the duration of irradiation to 0.0 s. The average transit dose per cycle is taken to be the ratio of the absorbed dose to the number of cycles.

3. Simulation procedure

GEANT4 is a software package composed of tools used to accurately simulate the passage of particles through matter (GEANT4 User's Guide, 2004). GEANT4 has been used in many applications, including simulation of high energy and nuclear physics experiments, radiation shielding, space radiation transport and effects, medical physics (GEANT4, 2002) and gamma irradiator design. The GEANT4 Object Oriented design allows the user to understand, customize or extend the toolkit in all domains. The platform used for the GEANT4 version 6.1 code was a Linux (Scientific Linux CERN 3) Personal Workstation.

The source geometry and material composition (Cobalt, Zirconium, Stainless steel …) were constructed in DetectorConstruction class. The detailed physics treatment for photon interactions are set in PhysicsList class. It also includes the electron-positron processes of multiple scattering, ionization, bremsstrahlung and annihilation (GEANT4 User's Guide, 2004). Dosimeters are spheres filled with water to be as close as possible to the dose measured by the PMMA dosimeters when put in air. After a random choice of pencil source (among 24 possibilities), the photons are generated uniformly from the cobalt pencils with a random momentum direction. The ^{60}Co isotope has two rays spontaneously emitted at 1.17 and 1.33 MeV. After collecting of the energy deposited in the dosimeters we convert it to absorbed dose. Statistical examinations showed that the most practical radius of these spheres is 0.5 cm which preserves a small statistical error (lower than 3%). The dose is straightforwardly calculated from the deposited energy in the water spheres along the run.

The dose rate $\dot{D}$ is calculated by transforming photon and electron deposited energies E_d inside the simulated dosimeter of mass m_d during a run of N events as follows:

$$\dot{D}(\mathrm{Gy/s}) = E_\mathrm{d}(\mathrm{MeV})\,\frac{2A(\mathrm{Bq})}{N}\,\frac{1}{m_\mathrm{d}(\mathrm{g})}\,6.21\times10^{9}, \tag{1}$$

where A is the source activity and the last factor at end of the equation convert the result from MeV/g to Gy unit. The factor 2 multiplying A is to take account of the two photon emission energies of ^{60}Co (1.17 and 1.33 MeV).

4. Calculated transit dose

The transit dose is the dose absorbed by the irradiated target, respectively, before interlocking (Fig. 1):

(1) displacement (62 cm) of the target from the initial position "*out*" towards the irradiation position "*in*" with a velocity v_c.
(2) displacement (24 cm) of the pencils from the storage position "*up*" towards the irradiation position "*down*" with a velocity v_p.

and after stopping of the stop timer controlling the duration of irradiation:

(3) displacement (62 cm) of the pencils from the irradiation position "*down*" towards the storage position "*up*" with a velocity v_p.
(4) displacement (24 cm) of the target from the irradiation position "*in*" towards position "*out*" with a velocity v_c.

This cycle lasts 20.4 s; 18.4 s for (1) and (3) and 2.0 s for (2) and (4). Thus, the transit dose D_T is the sum of the dose $D_{2,3}$ received during the rise and the descent of the pencils and $D_{1,4}$ received dose at the time of the displacement of the target.

To calculate $D_{2,3}$ we place 13 dosimeters on the z-axis. Two consecutive dosimeters are spaced by 2 cm. We vary the position of the pencils bary-center from $z = 0$ cm which corresponds to the irradiation configuration to the storage position ($z = 24$ cm) by steps of $\Delta z = 1$ cm for both loading/unloading of pencils. For each position we calculate the dose rate for the 13 dosimeters. To calculate $D_{1,4}$, pencils are now placed in the storage position ($z = 24$ cm). We vary the canister position according to the y direction from the position $y = 0$–62 cm by a step of $\Delta y = 1$ cm for both loading/unloading of canister. For each position, we calculate the dose rate using the 13 dosimeters. Transit dose for each dosimeter j is determined using the following expression:

$$D^j_{2,3} = 2\sum_{i=1}^{25} \dot{D}_{ij} \times \frac{\Delta z}{v_p}, \quad (2)$$

$$D^j_{1,4} = 2\sum_{i=26}^{88} \dot{D}_{ij} \times \frac{\Delta y}{v_c}, \quad (3)$$

where $\dot{D}_{ij}$ is the dose rate measured by the dosimeter j when the system is in configuration i.

5. Results and discussion

5.1. Validation of GEANT4 for the high dose case

Tow sets of measurements of the dose rates were realized in the irradiation cell. The first set of measurements of dose rates was realized for 13 points along the y-axis (horizontal direction). Comparison between predicted and experimental dose rate along the horizontal direction of the irradiation cell is shown in Fig. 3(a). Detailed behaviors are reproduced by simulation with a good accuracy.

The second set of measurements was performed using 18 dosimeters placed along a circle of radius 6.5 cm at $z = 0$ cm, the angle between two consecutive dosimeters is 20°. The absolute orientation of pencils inside the irradiator is not known. Therefore one can consider that dosimeter orientation is arbitrary with respect to the pencils. Monte Carlo simulation of this measurement requires 18 dosimeters in the same relative configuration considered in the experimental part. Since the absolute orientation of the dosimeters with respect to the pencils is not known, 36 simulations were realized to reach an angular resolution of 10°. In practice we start with an arbitrary orientation, to which we apply successive rotations of 10° to get the next configurations. Thus, each configuration corresponds to a rotation of an angle $\Delta\theta = 10°$ with respect to the preceding one. The best configuration corresponds to the minimal χ^2:

$$\chi^2 = \sum_{j=1}^{18} \frac{(D^j - D^j_k)^2}{\sigma^2}, \quad (4)$$

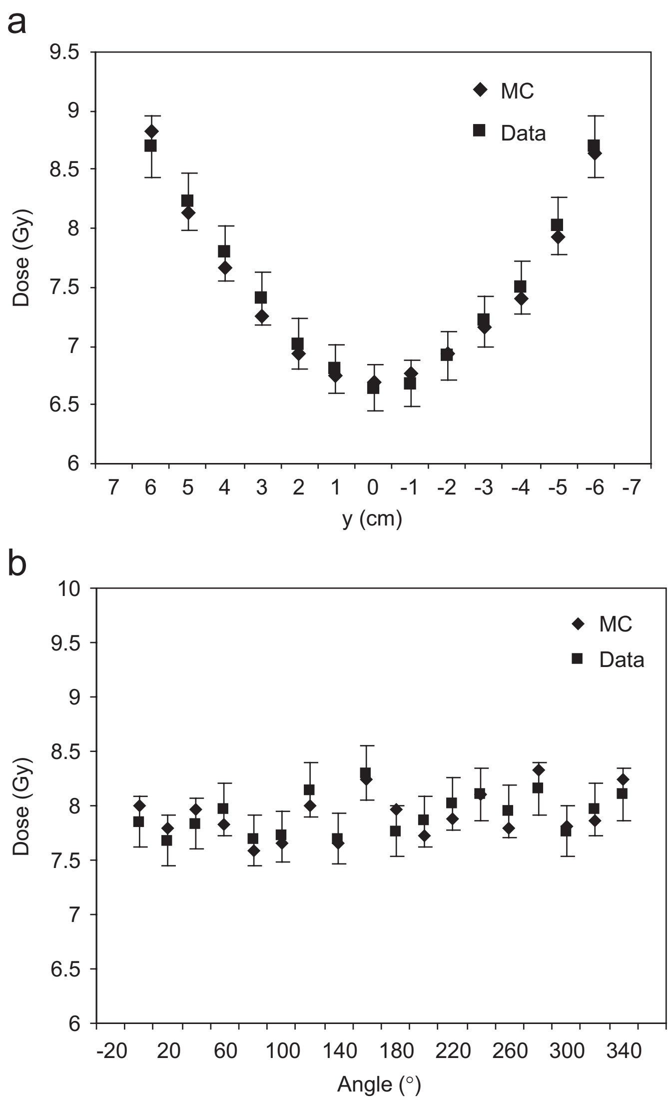

Fig. 3. (a) Calculated (MC) and measured (Data) dose along the horizontal y-axis; (b) Calculated and measured dose along a circle of radius 5.5 cm, for the simulated configuration with a minimal χ^2.

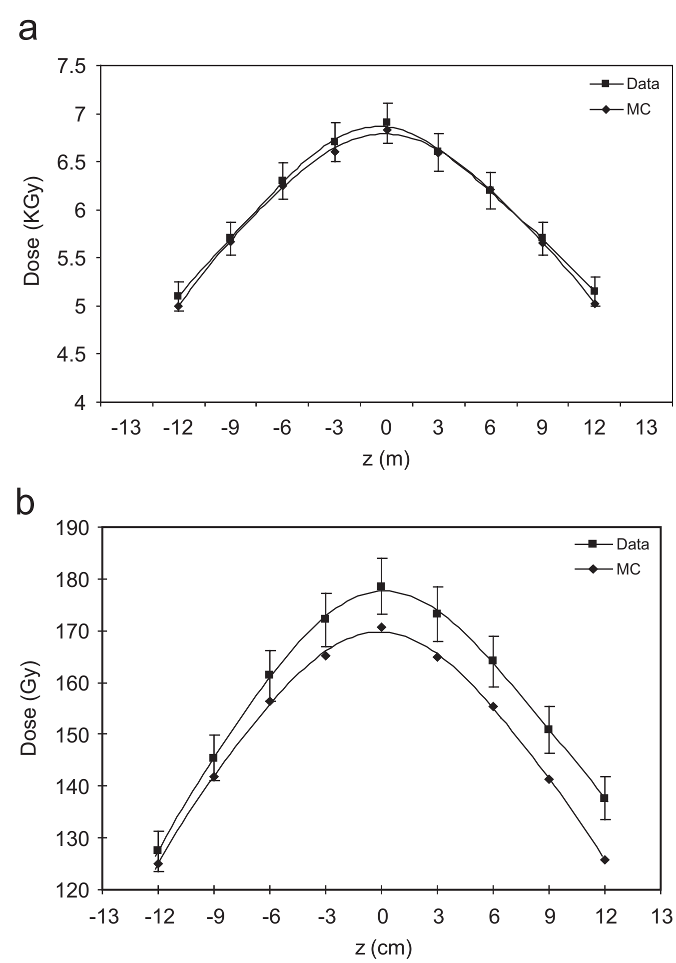

Fig. 4. (a) Calculated (MC) and measured (Data) dose along the vertical z-axis for high dose case. (b) Calculated (MC) and measured (Data) dose along the vertical z-axis for low dose case.

where D^j is the measured dose in dosimeter number j and D_k^j is the calculated dose in configuration k in the same dosimeter. σ^2 is the combined measured and calculated error.

Fig. 3(b) shows a comparison between experimental and simulated dose at $z = 0$ cm for the best configuration. The experimental dose is reproduced by the Monte Carlo simulation with a good agreement. Such satisfactory agreement between simulated and measured values of dose confirms that GEANT4 reproduces accurately the dose distribution in the irradiation cell.

5.2. Measured and calculated dose along z-axis for low and high dose cases

The measurement of dose rates was performed at nine points along the z-axis (vertical direction) for low and high dose cases. For the high dose case the experimental dose is reproduced well by the Monte Carlo simulation with a good agreement (Fig. 4(a)). The dose needed to ensure

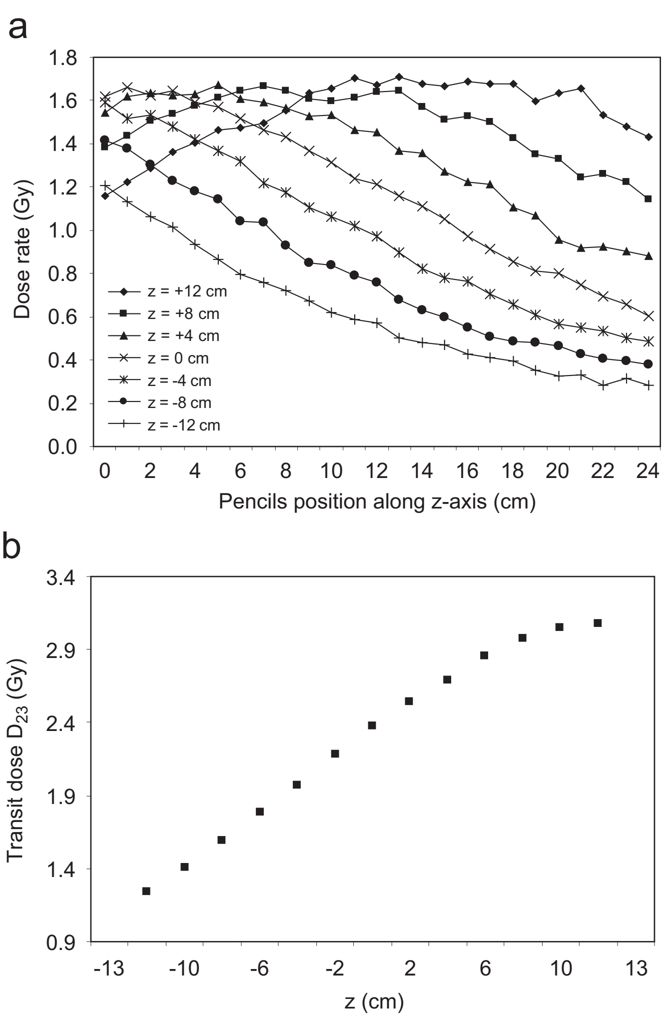

Fig. 5. (a) Calculated dose as measured by dosimeters placed, respectively, at $z = +12, +8, +4, 0, -4, -8, -12$ cm as function of the position of the pencils; (b) Transit dose rate received during the rise and the descent of pencils.

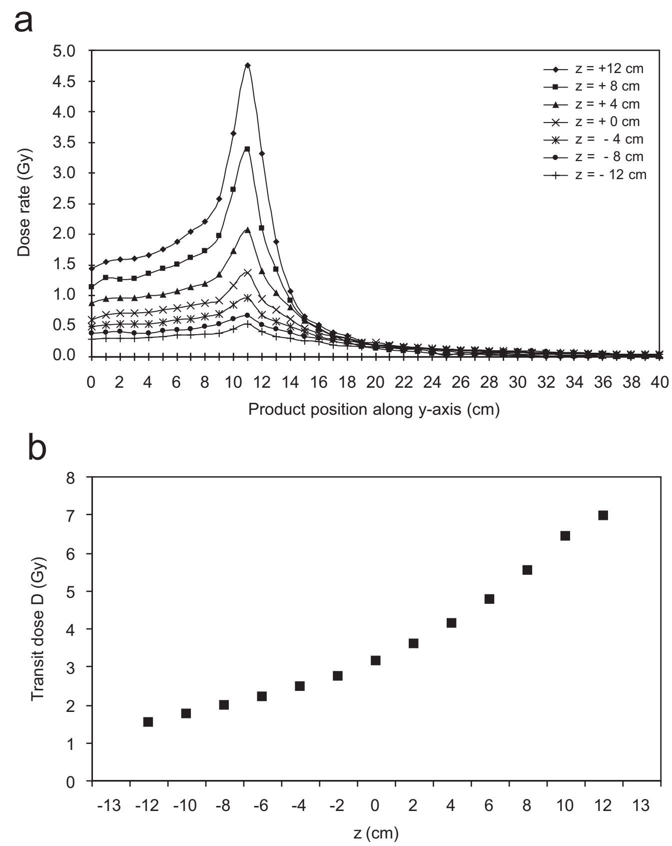

Fig. 6. (a) Calculated dose as measured by dosimeters placed, respectively, at $z = +12, +8, +4, 0, -4, -8, -12$ cm as function of the position of the target; (b) Transit dose rate received at the time of the displacement of the product.

Table 2
Measured and simulated transit dose at three points along the z-axis

z (cm)	Measured transit dose (Gy/cycle)	Simulated transit dose (Gy/cycle)
+12	10.6 ± 0.6	10.1 ± 0.3
0	5.2 ± 0.3	5.5 ± 0.2
−12	2.6 ± 0.2	2.7 ± 0.1

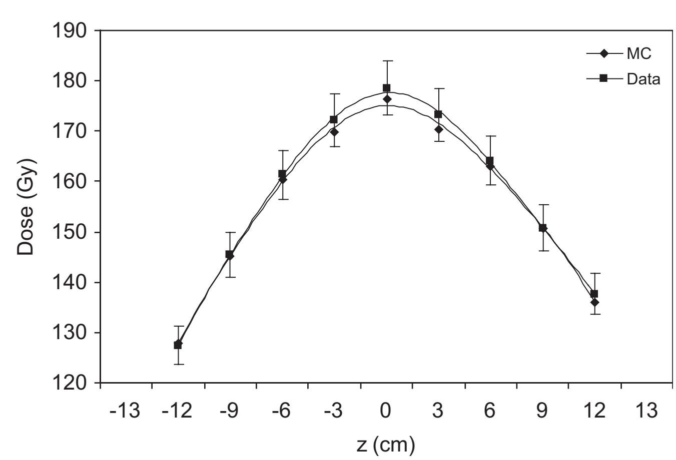

Fig. 7. Comparison between calculated and measured dose, taking into account the transit dose correction.

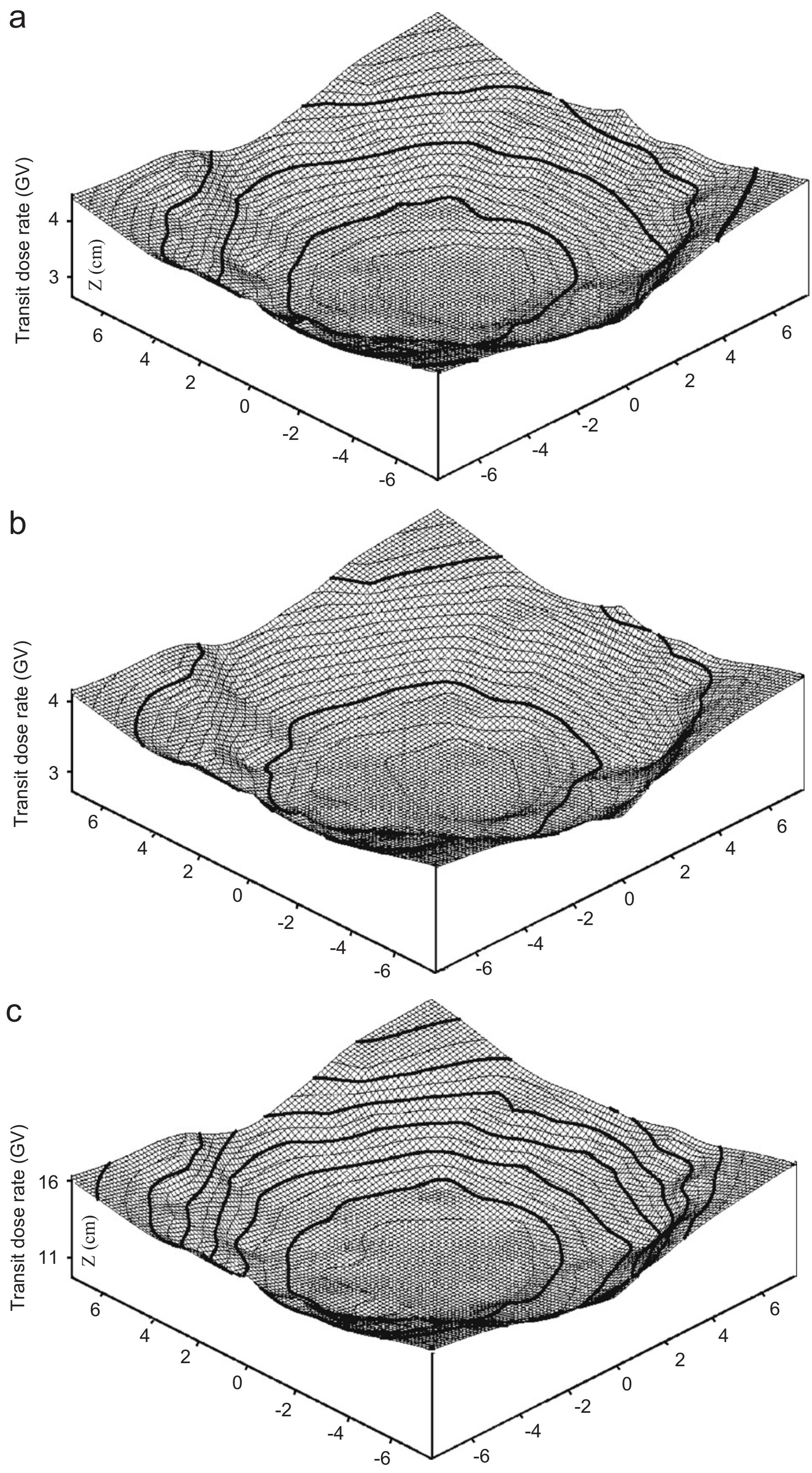

Fig. 8. Transit dose rate mapping, respectively, at horizontal plane ($z = 0, -12, +12$ cm).

99.5% sterility of treated insects is approximately 145–150 Gy (Walker et al., 1997). For doses as low as this, an asymmetry between the experimental and calculated values is observed (see Fig. 4(b)); this discrepancy increases from $z = -12$ to $+12$ cm. As we shall show below, this asymmetry is due to the transit dose.

5.3. Transit dose measurement and mapping

Fig. 5(a) shows the variation of absorbed dose by the dosimeters placed along the z-axis. The transit dose rate $D_{2,3}$ received by each dosimeter during the rise and the descent of pencils is represented in Fig. 5(b).

Variation of absorbed dose by dosimeters placed along the z-axis according to the position of the target y-axis is illustrated in Fig. 6(a). The overall transit dose received during the displacement, that is the sum of $D_{2,3}$ and $D_{1,4}$, is represented in Fig. 6(b).

Comparison between measured and calculated values in three points along the z-axis is given in Table 2. Measured transit dose is reproduced by Monte Carlo simulation with a good agreement. As showed in Fig. 7, taking into account the transit dose, the asymmetry between the experimental and calculated values for low dose is corrected.

To perform a full mapping, the transit dose rate is calculated with the same procedure described above in 131 points at three horizontal plane ($z = +12, 0, -12$ cm) of the irradiator. The maps are obtained by interpolation of the transit dose rate values. Figs. 8 shows the transit dose rate mapping obtained, respectively, in these plans for simulation results. The transit dose rate is low for $z = -12$ cm and increases with z and while moving towards the pencils.

6. Conclusion

In this work we illustrate the importance of transit dose which cannot be neglected at low dose irradiations. We show that it is necessary to take the variation of the transit dose into account according to the position inside the chamber of irradiation and the effect of this transit dose in the evaluation of the time of irradiation. The transit dose may be planned and must be considered and added to the prescribed dose. Taking into account of the transit dose, the dose rate in target was measured in different locations in the irradiation cell and successfully compared to the predicted results by Monte Carlo simulation using the GEANT4 code of CERN.

Acknowledgments

Thanks to O. Kadri and F. Gharbi for many good suggestions that have improved earlier version of the manuscript. We are also grateful for K. Farah and F. Kuntz for their help in conducting dosimetric measurements.

References

Aer'ODE v2.1.1, Optical Dosimetry readout Equipment software.

Bogaerts, R., Esch, A.V., Reymen, R., Huyskens, D., 2000. A method to estimate the transit dose on the beam axis for verification of dose delivery with portal images. Radiotherapy and Oncology 54, 39–46.

Calcina, C.S.G., Almeida, A., Rocha, J.R.O., Abrego, F.C., Baffa, O., 2005. Ir-192 HDR transit dose and radial dose function determination using alanine EPR dosimetry. Physics in Medicine and Biology 50, 1109–1117.

Follett, P.A., 2004. Irradiation to control insects in fruits and vegetables for export from Hawaii. Radiation Physics and Chemistry 71, 161–164.

GEANT4, 2002. A simulation toolkit. GEANT4 Collaboration, SLAC-PUB-9350, August.

GEANT4 User's Guide, 2004. For Application Developers. V.GEANT4 6.1, March.

Gharbi, F., Kadri, O., Farah, K., Mannai, K., 2005. Validation of GEANT4 of cern as predictive tool of dose rate measurement in the Tunisian gamma irradiation facility. Radiation Physics and Chemistry 74, 102–110.

Hallman, G.J., 1999. Ionizing radiation quarantine treatments against tephritid fruit flies. Postharvest Biology and Technology 16, 93–106.

Oliviera, C., Ferreira, L.M., Gonçalves, I.F., Salgado, J., 2002. Monte Carlo studies of the irradiator geometry of the Portuguese Gamma Irradiator Facility. Radiation Physics and Chemistry 65, 293–295.

Soharabpour, M., Hassanzadeh, M., Shahriari, M., Sharifzadeh, M., 2002. Dose distribution of the IR-136 irradiator using a Monte Carlo code and comparison with dosimetry. Radiation Physics and Chemistry 63, 769–772.

Walker, M.L., Mclaughlin, W.L., Puhl, J.M., Gomes, P., 1997. Radiation-field mapping of insect irradiation canisters. Applied Radiation and Isotopes 48 (1), 117–125.

Wojcicka, J.B., Yankelevich, R., Trichter, F., Fontenla, D.P., 1999. Comparison of the transit dose components and source kinematics of three high dose rate afterloading systems. Medical Dosimetry 24 (1), 61–65.