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Calculation of dose uniformity ratio in irradiation cell of GC-220 using analytical method based on multipole moment expansion

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HIGHLIGHTS

- The dose uniformity ratio DUR is calculated using the analytical method.
- The analytical method was based on multipole moment expansion.
- The DUR in radiation cell of GC-220 was calculated using Monte Carlo simulations.
- The difference between values of DUR calculated by the analytical and simulation is less than 12%.
- The consistency between calculations and Monte Carlo simulations validates the presented method.

ABSTRACT

In this paper, dose uniformity ratio in irradiation cell of GC-220 is specifiedutilizing an analytical method based on the multipole moment expansion. In this method, the values of monople, dipole and quadrupole moments for source arrangements of GC-220 are calculated by numerical integrating. Appling these values, the dose uniformity ratio in the irradiation cell of GC-220 is calculated equal to 1.92. Monte Carlo simulation is applied to validate calculations. There is a relative difference about 12% between the results obtained from the analytical calculation and Monte Carlo simulation, which confirm the used method. In comparison with Monte Carlo methods, this method is not time consuming, so, this method can be used for the conceptual designing and the source load planning of irradiators.

KEYWORDS
Dose Uniformity Ratio
Mutipole Moment Expansion
Monte Carlo Method
Gamma Cell 220
Source Load Planning

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1 Introduction

Nowadays, ionization radiations have been extensively applied in various fields such as industrial (Farah et al., 2006; Sharpe et al., 2000), research (Akhavan et al., 2014), agriculture (Solanki et al., 2012), medical purposes (Soliman et al., 2013; Gual et al., 2013). Industrial or research gamma irradiators may be utilized to irradiate a sample or product based on the volume of it and the absorbed dose value (Gual et al., 2013; Vandana et al., 2011; Cummins and Delaney, 1961). To use an irradiator, it is necessary to know some characteristics such as dose uniformity ratio (DUR). So, different simulation and experimental methods have been employed to specify this ratio for different irradiators.

In 1990, dosimetric studies were performed by Chu at a number of industrial gamma irradiators to determine the DUR for optimizing the irradiating process (Chu, 1990). In other research in this year, Raisali et al. calculated the DUR for IR-136 irradiation facility using a computer code based on the point kernel method (Raisali et al., 1990). Oliveira and Salgado used MCNP code to determine the DUR in the Portuguese gamma irradiation facility (Oliveira and Salgado, 2001). Moreover, for Tunisian gamma irradiation facility, the DUR was specified using GEANT4 toolkit and compared with values measured by Red Perspex dosimeters (Kadri et al., 2005). In addition, the DUR of this facility was determined utilizing CTA, Amber and Red Perspex dosimeters in a similar research (Farah et al., 2006). In 2013, radiochromic films were employed to determine the DUR in irradiation gamma facility (Soliman et al., 2013).

Rezaeian at al. presented an analytical method based on the multipole moment expansion to calculate the flux distribution (Rezaeian et al., 2017). In present paper, this method is used to determine the DUR inside the radiation cell of gammacell-220 (GC-220) and compared with Monte Carlo N-Particle transport code (MCNP4C) simulations.

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2 Materials and Methods

2.1 Gammacell Irradiator (GC-220)

GC-220 is used to irradiate small samples for research purposes. This irradiator consists of a cylindrical irradiation cell made of aluminum. The radius (R) and height (H) of this cell is 7.5 and 20 cm, respectively. The irradiation cell is surrounded by the source including 21 cylindrical Co-60 pencils with radius and height of 0.32 and 19.63 cm, respectively. Theses pencils are located in a cylindrical steel cage with diameter of 20.91 cm. Cross view of the irradiation cell and the related cage are depicted in Fig. 1.

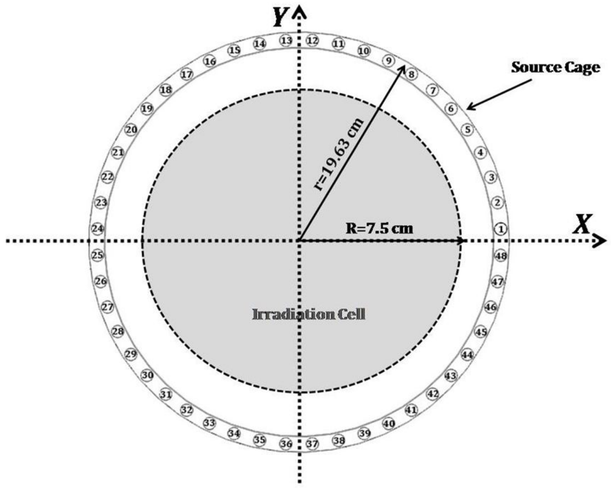

Figure 1: Cross view of the source cage and irradiation cell of GC-220.

As shown in Fig. 1, the source cage consists of 48 source pencils positions with height of 21.11 cm. These positions are parallel to Z-axis and the activity distribution of each pencil is uniform. Consequently, the source of GC-220, with respect to Z-axis is symmetric. The position number and the activity of these sources in April, 1, 2016 are tabulated in Table 1. It should be noted that the total activity of the source is 8981 Ci.

2.2 Analytical Method

The flux of photons in each point of the irradiation cell is written as (Rezaeian et al., 2017):

$$\varphi(\vec{r}) = \frac{1}{4\pi}[\mu + 2\sum x_i\rho_i + \sum(4x_ix_j - \delta_{ij}r^2)\ell_{ij} + ...] \tag{1}$$

where μ, ρ and ℓ_{ij} are the monopole, dipole and quadrupole moments, respectively. The values of multipole moments are given by:

$$\mu = \int_\Omega \frac{\rho_A(\vec{r'})}{r'^2}\mathrm{d}^3r' \tag{2}$$

$$\rho_i = \int \frac{x'_i\rho_A(\vec{r'})}{r'^4}\mathrm{d}^3r' \tag{3}$$

$$\ell_{ij} = \int \frac{x'_ix'_j\rho_A(\vec{r'})}{r'^6}\mathrm{d}^3r' \tag{4}$$

where $\rho_A(r)$ is the activity density of source and r' is the distance of volume element of d^3r' from the origin. In this paper, the origin is considered as the center of the irradiation cell. Also, x'_i is the Cartesian component of r'. It is obvious from Eqs. (2-4) that the values of mutilpole moment depend on the arrangement of the source. As it shown in Fig. 1, the source of GC-220 is symmetric with respect to Z-axis. So, according to Eqs. (2-4), it can be shown that $\ell_{xz} = \ell_{yz} = 0$ and $\rho_z = 0$. As shown in (Rezaeian et al., 2017), the flux in vicinity of the side wall of irradiation cell is higher than in center and the value of flux above or below the irradiation cell is lower than the center. Consequently, the locations of the maximum flux are placed on a circle with radius of R in plane of $Z = 0$. Further, the positions of minimum flux are located in the center of $Z = \pm H/2$ planes. One of the maximum flux points can be considered as $(R, 0, 0)$. Using Eq. (1), the value of flux in this point can be written as:

$$\varphi_{\max}(\vec{r}) = \frac{1}{4\pi}\left[\mu + 2R\rho_x + R^2(3\ell_{xx} - \ell_{yy} - \ell_{zz})\right] \tag{5}$$

Moreover, the coordinate of minimum flux point on the top of the irradiation cell is $(0, 0, H/2)$. The value of the flux in this point is:

$$\varphi_{\min}(\vec{r}) = \frac{1}{4\pi}\left[\mu + H\rho_z + \frac{H^2}{4}(3\ell_{zz} - \ell_{xx} - \ell_{yy})\right] \tag{6}$$

Using of Eqs. (5-6), the DUR can be expressed as:

$$DUR = \frac{\varphi_{\max}(\vec{r})}{\varphi_{\min}(\vec{r})} = \frac{\mu + 2R\rho_x + R^2(3\ell_{xx} - \ell_{yy} - \ell_{zz})}{\mu + H\rho_z + \frac{H^2}{4}(3\ell_{zz} - \ell_{xx} - \ell_{yy})} \tag{7}$$

Using Eq. (7), the DUR for GC-220 can be determined analytically. It should be mentioned that in order to simplify the calculations in derivation of Eq. (7), points of $(R, 0, 0)$ and $(0, 0, H/2)$ are considered as locations of maximum and minimum flux, respectively. Due to the symmetric arrangements, the DUR values are the same in the other planes crossing the center of the cell as well as in the planes perpendicular to the upper and lower planes of the cylindrical cell.

Table 1: Activity of the source pencil of GC-220.

Number of Pencil	1	4	7	8	11	13	14	17	19	20	24
Activity (Ci)	1052.3	40.7	1057.6	40.7	33.9	1052.3	42.6	33.9	1029.3	42.6	40.7
Number of Pencil	25	28	31	32	36	37	40	43	44	48	
Activity (Ci)	1065.2	40.7	1049.9	40.7	40.7	1073.3	41.0	1081.0	41.0	40.9	

2.3 MCNP Calculations

MCNP4C (Briesmeister et al., 2000) was used for simulating the GC-220. The geometry and composition of materials used in GC-220 were implemented in the code according to the manual of GC-220. The flux values in different points inside the cell were calculated by F4 tally and by dividing the maximum flux to minimum flux obtained from the plotted curves to calculate the DUR of the intended planes. The number of particles generated uniformly from the simulated source with the random direction is selected on such a way that the relative uncertainty due to the statistical error is smaller than 1%.

3 Results

To calculate DUR, the values of monopole, dipole and quadrupole moments were calculated by the numerical integrating. The calculated values for each pencil as well as the total values are tabulated in Table 2.

Using the values of multipole moment shown in Table 3 and Eq. (1), the flux distribution in planes of XZ and YX was mapped as shown in Fig. 2. For mapping the flux, the values of flux at each point of the irradiation cell were normalized with respect to the flux at the center of irradiation cell. As shown in Fig. 2, due to the symmetry of source pencils with respect to Z axis and symmetric arrangement of the source pencils in XY plane, the flux has a symmetric distribution in XY plane.

Using Eq. (1), the values of absolute flux in the center of the irradiation cell as well as the maximum and minimum relative flux were determined analytically. Further, using Eq. (7), the DUR in the irradiation cell was calculated. To validate the analytical method, the values of absolute flux as well as the maximum and minimum relative flux are calculated by Monte Carlo simulation. The values calculated by the analytical and simulation methods are compared in Table 3.

As shown in Table. 3, the calculated flux in the center of the irradiation cell using analytical method is in consistence with value obtained by Monte Carlo simulation. Furthermore, the relative difference between the calculated values of maximum and minimum relative flux and DUR and the simulated ones are less than 12%.

4 Conclusion

The consistency between the calculated results using analytical method and Monte Carlo simulation confirm the analytical method. Using the analytical method based on the multipole moment expansion, the dose uniformity ratio can be calculated faster than using Monte Carlo methods such as MCNP code. Regarding that, the DUR is one of the important parameters of irradiators, this analytical method can be useful to determine DUR in conceptual designing of irradiators or new source loading.

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Table 2: The values of multipole moments calculated for each pencil and total value of GC-220. Due to symmetry of source respect to $Z-$axis $\ell_{xz} = \ell_{yz} = 0$ and $\rho_z = 0$. μ in (TBq cm^2), ρ in (TBq cm^{-3}) and ℓ in (TBq cm^{-4}).

Pencil Number	μ	ρ_x	ρ_y	ℓ_{xx}	ℓ_{yy}	ℓ_{zz}	ℓ_{xy}
1	3.58E − 01	2.81E − 02	1.84E − 03	2.00E − 03	1.05E − 05	3.82E − 04	1.49E − 04
4	1.39E − 02	9.82E − 04	4.84E − 04	6.47E − 05	1.74E − 05	1.48E − 05	3.52E − 05
7	3.59E − 01	1.87E − 02	2.13E − 02	1.04E − 03	1.30E − 03	3.84E − 04	1.14E − 03
8	1.39E − 02	6.09E − 04	9.10E − 04	3.17E − 05	6.15E − 05	1.48E − 05	4.10E − 05
11	1.16E − 02	1.79E − 04	8.96E − 04	1.14E − 05	7.13E − 05	1.24E − 05	1.42E − 05
13	3.58E − 01	−1.83E − 03	2.81E − 02	2.94E − 04	2.28E − 03	3.82E − 04	−1.49E − 04
14	1.45E − 02	−2.23E − 04	1.12E − 03	1.43E − 05	8.95E − 05	1.55E − 05	−1.78E − 05
17	1.16E − 02	−5.07E − 04	7.60E − 04	2.65E − 05	5.13E − 05	1.24E − 05	−3.42E − 05
19	3.50E − 01	−2.08E − 02	1.82E − 02	1.23E − 03	9.75E − 04	3.74E − 04	−1.11E − 03
20	1.45E − 02	−9.52E − 04	6.36E − 04	5.99E − 05	2.87E − 05	1.55E − 05	−4.29E − 05
24	1.39E − 02	−1.09E − 03	7.16E − 05	7.75E − 05	4.07E − 07	1.48E − 05	−5.80E − 06
25	3.62E − 01	−2.85E − 02	−1.87E − 03	2.02E − 03	1.06E − 05	3.87E − 04	1.51E − 04
28	1.39E − 02	−9.82E − 04	−4.84E − 04	6.47E − 05	1.74E − 05	1.48E − 05	3.52E − 05
31	3.57E − 01	−1.86E − 02	−2.12E − 02	1.03E − 03	1.29E − 03	3.81E − 04	1.13E − 03
32	1.39E − 02	−6.09E − 04	−9.10E − 04	3.17E − 05	6.15E − 05	1.48E − 05	4.10E − 05
36	1.39E − 02	−7.20E − 05	−1.09E − 03	1.14E − 05	8.85E − 05	1.48E − 05	5.80E − 06
37	3.65E − 01	1.87E − 03	−2.87E − 02	3.00E − 04	2.33E − 03	3.89E − 04	−1.52E − 04
40	1.40E − 02	4.87E − 04	−9.88E − 04	2.43E − 05	7.20E − 05	1.49E − 05	−3.55E − 05
43	3.68E − 01	2.18E − 02	−1.91E − 02	1.29E − 03	1.02E − 03	3.92E − 04	−1.17E − 03
44	1.40E − 02	9.16E − 04	−6.12E − 04	5.76E − 05	2.76E − 05	1.49E − 05	−4.13E − 05
48	1.39E − 02	1.09E − 03	−7.16E − 05	7.75E − 05	4.07E − 07	1.48E − 05	−5.80E − 06
Total	3.05E + 00	5.68E − 04	−7.08E − 04	9.76E − 03	9.80E − 03	3.26E − 03	−2.19E − 05

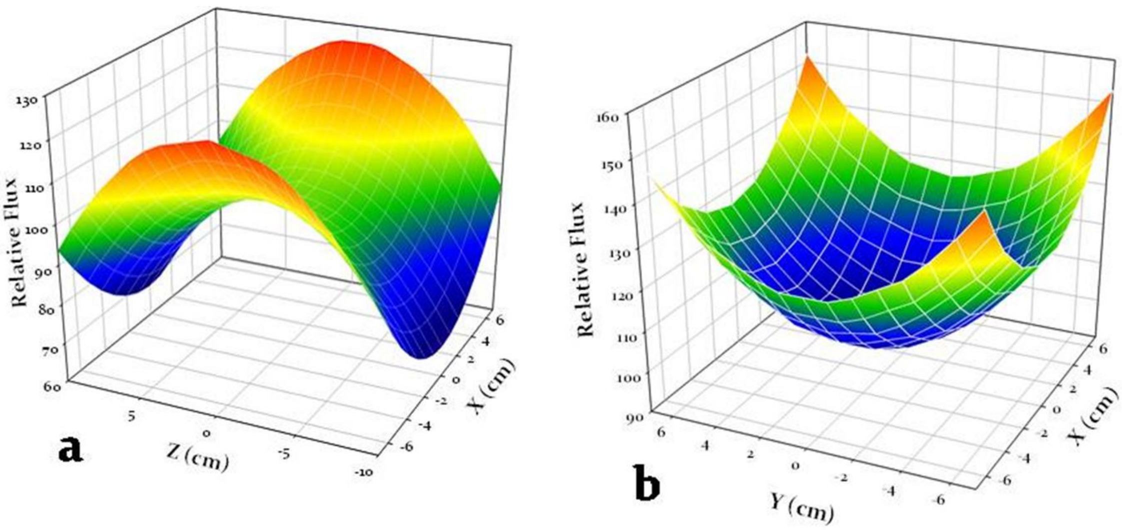

Figure 2: The flux distribution in the irradiation cell of GC-220 mapped in (a): XZ and (b): YX planes. The values of flux in each pointare normalized to flux in center of cell.

Table 3: Comparison of values calculated by analytical and simulation method for GC-220.

Quantity	Analytical Method	MCNP simulation
Flux in the center of irradiation cell ($cm^{-2}.s^{-1}$)	4.86×10^{11}	$(4.86 \pm 0.02) \times 10^{11}$
Maximum Relative Flux (%)	130.0	136.61 ± 0.79
Minimum Relative Flux (%)	67.9	75.66 ± 0.44
Dose Uniformity Ratio	1.92	1.81 ± 0.90

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