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Investigation for Monte Carlo simulation with geometric simplification of the GammaCell 220 irradiator with experimental measurements using Fricke xylenol gel (FXG)

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ABSTRACT

Radiation therapy necessitates dosimetry using materials with densities similar to human tissue and at a lower cost. Comparisons with simulation methods will help validate new dosimeters and their measurements. To experimentally simulate radiation effects, an industrial irradiator like the GammaCell 220 can be utilized. This study aims to validate FXG dosimetry through Monte Carlo simulations using the MCNP and TOPAS codes, employing a simplified geometry model of the GammaCell 220 irradiator. The FXG dosimeter demonstrated linearity with an R^2 of 0.99517. Monte Carlo simulations using both codes showed coherence, with MCNP exhibiting greater similarity to experimental results. The incorporation of simplified Monte Carlo modeling demonstrates the feasibility of obtaining satisfactory results for the GammaCell 220 irradiator geometry. Additionally, it validates the applicability of FXG dosimetry for future utilization in radiation therapy.

1. Introduction

The use of irradiators is essential tool to validate and simulate doses in radiation therapy, ensuring the effectiveness and safety of oncological treatments. To improve measurements in such a precise area as dosimetry, it is essential to use low-cost and easy-to-operate dosimeters. Furthermore, it is crucial to employ materials with a density similar to that of the human body, thus ensuring the accuracy and relevance of the results obtained. These materials and devices are indispensable for ensuring that the radiation doses administered during treatments are effective and safe, faithfully reflecting the conditions found in the human body (Schreiner, 2015).

Monte Carlo simulation assumes an important role in assessment and optimization of irradiators, serving a pivotal function in various applications from radiotherapy to nuclear physics research (Andreo, 1991; Andreo, 2018; Knoll et al., 2022). This represents a crucial phase in validating experimental dosimetry parameters. During simulation, incorporating the complete geometry of the radiation-emitting apparatus, such an irradiator, into the Monte Carlo code is necessary. Depending on the irradiator, this task can be challenging, hindering straightforward verification.

The GammaCell 220 irradiator, renowned for its effectiveness in various fields, stands out as an essential component in studies involving interactions with ionizing radiations. At the Nuclear and Energy Research Institute (IPEN-CNEN), located in São Paulo, Brazil, it assumes a crucial role in scientific research by irradiating materials such as blood, cells, food, and test subjects. Its applications include radiosterilization, pest control, processing, and simulation of radiotherapy in small volumes. However, the accuracy of Monte Carlo simulations associated with GammaCell 220 is intricately linked to the quality of geometric modeling (Yan et al., 2015).

The modeling of this irradiator presents challenges due to its complex geometry, which includes rods composed of metal alloys and cobalt-60 capsules. The presence of rods with different levels of activity, or even the absence of the source in some rods, can result in a non-uniform distribution of activity in the irradiator. However, the Atomic

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Energy of Canada Limited (AECL) company that provides the equipment, conducts dosimetric tests to ensure that a specified dose is 100% consistent in the center of the irradiator. Additionally, quality control tests provide detailed information about isodose curves, measured through an ionization chamber (Raisali and Sohrabpour, 1993).

The complexity of the geometries employed in simulations can directly impact computational efficiency and the accuracy of obtained results. In this context, this study proposes an investigation into geometric simplification applied to the Monte Carlo simulation of the GammaCell 220 irradiator and a validation of the Fricke xylenol gel (FXG) dosimetry to be used in radiation therapy. The aim is to analyze the feasibility of simulating a simplified model of a 1970s irradiator still in use in scientific research. Using a simpler geometry to simulate a real situation not only reduces simulation time but also facilitates implementation and maintenance by minimizing the likelihood of errors during coding and execution.

A distinctive feature of this work is the integration of experimental measurements using FXG dosimeter, also serving as the target of interest for dose simulation. This approach not only provides experimental validation of current calibration for low doses but also yields valuable insights into the agreement between simulated results and actual measurements. By incorporating experimental data, we seek to enhance the reliability and quality of the results obtained through Monte Carlo simulation.

2. Material and methods

The methodology of this work begins with the characterization of the GammaCell 220 irradiator, which plays a central role as the radiation source in this study. Understanding its specifications and performance parameters is crucial for subsequent dosimetric measurements and simulations. Next, attention turns to the FXG dosimeter, a critical component for experimental measurements, where its production method and characterization are defined. With the experimental setup established, Monte Carlo simulations are conducted to model the geometry of the irradiation setup. This step involves using the MCNP and TOPAS codes to simulate the interaction of radiation with the FXG dosimeter and surrounding materials.

2.1. Gammacell 220 irradiator

Gammacell 220 is a cobalt-60 irradiator manufactured by the AECL company for use in an unshielded room. According to the manual, the unit consists of a circular arrangement permanently enclosed in a lead shielding, and a cylindrical drawer with a drive mechanism to move it up or down along the central axis of the source. The source cage is positioned at the center of the irradiator, containing 48 rods arranged in a circular arrangement, each with 7 completely sealed and welded cobalt-60 capsules (Fig. 1).

This irradiator is widely used in scientific research and laboratory applications. The Gammacell 220 allows for the simulation of controlled radiation conditions, the study of biological effects of radiation, and the conduct of cancer-related research (Moradi et al., 2017).

While each Gammacell 220 may vary in terms of load capacity, dose rate, exposure control, and other specific features, overall, it is important in research requiring controlled exposure to ionizing radiation in laboratory settings (AECL, 1974). For the purpose of this study, the source activity was 1.5×10^7 Bq, with a dose rate of 343.47 Gy/h at the center for small volumes.

2.2. Fricke xylenol gel dosimeter (FXG)

The FXG is a radiochromic dosimeter that utilizes an aqueous solution of ferrous sulfate. When irradiated, this system oxidizes ferrous ions (Fe^{+2}) to ferric ions (Fe^{+3}) through the radiolysis of the aqueous system (Fricke and Morse, 1927). To serve as an indicator of ferric ions in the irradiated volume, it is necessary to introduce a coloring agent into the gel matrix, such as xylenol orange. This dye imparts coloration to the Fricke solution, ranging from orange to violet as the quantity of ferric ions increases, reflecting the applied dose (Otomo, 1965).

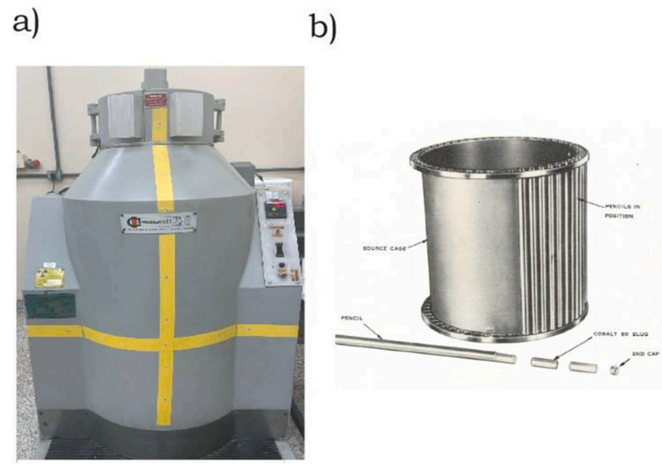

Fig. 1. a) Overall view of GammaCell 220 and **b)** Internal cage with demonstration of cobalt-60 source rods with support for source immobilization and protection (AECL, 1974).

The method was performed based on Del Lama et al. (2013), with modifications in the stoichiometry. After weighing the reagents, ultrapure water is divided into two parts (75% and 25%). In the 75% portion, bovine commercial gelatin 270 Bloom is added, dissolved, and heated to 55 °C. The homogenization temperature is adjusted to 45 °C, and ammoniacal ferrous sulfate (Synth®), sulfuric acid (Sigma-Aldrich), and xylenol orange (Synth®) are added, previously dissolved in the remaining 25% volume of ultrapure water. After solution homogenization, the liquid is placed in acrylic cuvettes in the refrigerator to achieve a gel-like consistency.

The FXG is used in laboratories for dosimetry studies in radiotherapy due to its equivalence to water or soft tissue in a diverse range of photon energies (Chan and Ayyangar, 1995). Consequently, the dosimeters were irradiated with doses of 5, 10, 20, and 30 Gy in the GammaCell 220 irradiator at room temperature to assess the linearity of ferric ion absorbance, as the irradiator is used for simulating radiotherapy in small volumes.

Color variation is measured using the ultraviolet–visible absorption spectroscopy technique (Shimadzu UV-1800), scanning from 350 to 650 nm at room temperature. The UV–Vis technique quantifies absorbance at a specific wavelength. By measuring absorbance at different wavelengths, it is possible to establish a correlation with the color variation of a compound. This provides an understanding of the occurring electronic transitions and the specific regions of the electromagnetic spectrum that are absorbed (absorbance) or transmitted (transmittance). In this context, the observations will be related to Fe^{2+} and Fe^{3+} ions (Gupta et al., 1985).

2.3. Monte Carlo simulations (geometry)

The geometry of the GammaCell 220 irradiator, used for simulation in this study, consists of an external lead cylinder with dimensions of 120.65 cm in height and 50.80 cm in radius. Within this lead cylinder, the cobalt-60 radiation source is positioned, represented by an isotropic cylindrical shell with dimensions of 20.65 cm in height and 7.74 cm in radius. The Fricke dosimeter sample was positioned at the center of the source for analysis, the dosimeter consists of a 3 ml solution contained in an acrylic (PMMA) cuvette with approximately 3.5 cm^3 and 1 mm thickness, as illustrated in Fig. 2. For the simulation, the two characteristic energy peaks of cobalt-60 were considered, which are 1.17321

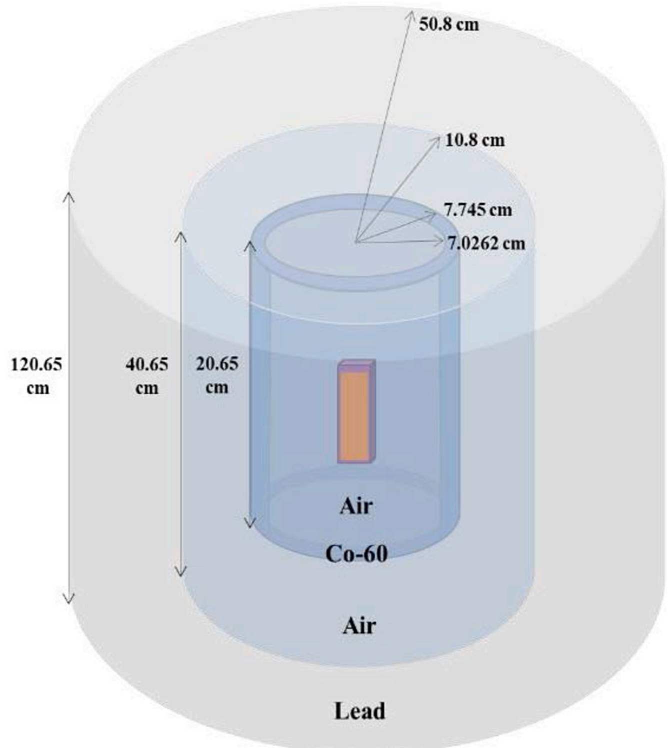

Fig. 2. Representation of the geometry employed in the MCNP and TOPAS codes of irradiator GammaCell-220.

MeV and 1.33249 MeV, with emission probabilities of 0.9986 and 0.9998, respectively. Table 1 provides information on the density and composition of the materials used in the simulations.

Another observation that is important to mention is that in Table 1, where the composition of the Fricke dosimeter modeled by Monte Carlo differs from that employed in the proprietary production methodology. However, it is crucial to note that these differences become negligible due to the proximity of the density values of the two materials. This similarity does not lead to perceptible differences in this simulation (Austerlitz et al., 2007; Uzorka et al., 2022).

2.4. MCNP® code

The MCNP is a versatile computational tool capable of simulating a broad range of ionizing radiations, such as neutrons, photons, and electrons, among others. Its application is particularly valuable for solving complex problems that cannot be effectively addressed by deterministic methods (Briesmeister, 2000).

By sequentially simulating probabilistic events, MCNP employs statistical sampling techniques to describe the phenomenon comprehensively. The version used in this study was MCNP version 4C (Briesmeister, 2000), and the MCNP input file, the tally F6 was employed to record the energy deposited per unit mass for each simulated particle (in units of MeV/g per particle).

A simulation was conducted using the Fricke dosimeter centered at (0,0,0), along with 11 additional simulations varying the position of the dosimeter to compare the isodose curves obtained from the simulation with those obtained from the GammaCell. 10^6 histories were simulated, with an uncertainty of $1{,}62 \times 10^{-5}$. The physics used in this case was the default of MCNP, thus secondary particles were considered.

2.5. TOPAS code

The TOPAS tool is an innovative code designed as a Geant4 framework, incorporating advanced and reliable tools experimentally validated and designed for ease of use. Moreover, TOPAS enables state-of-the-art research, ranging from detailed and accurate dose calculations for patients to simulations of detectors under development for particle computed tomography (Perl et al., 2012).

TOPAS, version 3.8, encompasses and extends the functionality of Geant4, and in the present study, simulations were performed using the EnergyDeposit scorer. This scorer is defined for the geometric component and an active material of interest, which is the Fricke dosimeter. For this code, 10^6 histories were also simulated, with an uncertainty of 1.09×10^{-5}, to compare the codes with the same parameters.

To perform the simulations, the default physics and library of TOPAS were used. The g4em-standard_opt4 model was employed to achieve high precision in electromagnetic processes, including ionization and bremsstrahlung. For managing inelastic nuclear interactions and elastic neutron scattering below 20 MeV were managed using the g4h-phy_QGSP_BIC_HP physics list. Furthermore, the decay of cobalt-60 nuclei was simulated using g4decay to ensure accurate representation of the decay processes.

3. Results and discussion

The FXG dosimeter has a simple methodology (described in Section 2.2), and with the addition of the orange xylenol dye it is possible to visually observe the different colors of the dosimeter after production and irradiation (Fig. 3).

The ferric ions are related to the absorbed dose. In light of this, cuvettes containing FXG were measured using a UV–Vis spectrophotometer, establishing a relationship between absorbance and wavelength. The results are presented in Figs. 4 and 5.

While the band at 436 nm, associated with ferrous ions, is decreasing, conversely, the band at 577 nm, related to Fe^{3+}, is increasing. As the applied dose in the dosimeter increases, Fe^{2+} ions undergo oxidation, reducing their concentration and increasing the concentration of Fe^{3+} ions, thereby correlating with the absorbed dose in the FXG (Gupta et al., 1985). This increase in deposited energy in that volume shows a linearity between absorbance and dose. In this context, these results agree with findings already documented in the literature (Liosi et al., 2017).

Table 1
Density, composition and atomic number of the six materials used in this work, compositions are in fraction by weight (PNNL, 2021).

Fraction by Weight												
Material	Density g/cm^3	Element and Atomic Number										
		H	C	N	O	Na	S	Cl	Ar	Fe	Co	Pb
		1	6	7	8	11	16	17	18	26	27	82
Air	0.001205	–	0.00015	0.78443	0.21075	–	–	–	0.00467	–	–	–
Lead	11.35	–	–	–	–	–	–	–	–	–	–	1.00000
Cobalt	8.86	–	–	–	–	–	–	–	–	–	1.00000	–
PMMA	1.19	0.53333	0.33333	–	0.13333	–	–	–	–	–	–	–
Water	1.00	0.66667	–	–	0.33333	–	–	–	–	–	–	–
Fricke	1.024	0.66001	–	0.00001	0.33748	0.000006	0.002485	0.000006	–	0.000006	–	–

Fig. 3. Photograph of disposable acrylic cuvettes with non-irradiated (0 Gy) and irradiated FXG solutions with 5, 10, 20 and 30 Gy (from left to right).

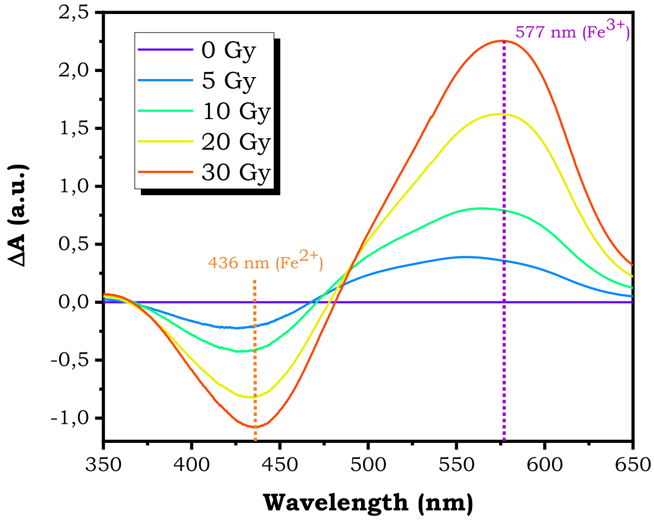

Fig. 4. Spectra of the UV-VIS absorption variation of FXGs produced and irradiated for absorbed doses of up to 30 Gy.

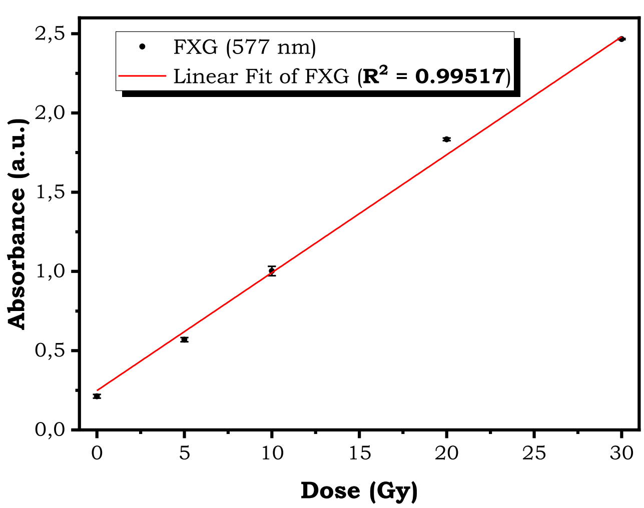

Fig. 5. FXG standard calibration curve of absorbance in relation to the dose obtained at 577 nm. Error bars are included in the bullet size.

From the linear fitting, it was possible to extract parameters of the linear regression and identify the values of the slope and intercept of the line, as well as the coefficient of determination. The coefficient of determination, often denoted as R^2, is a statistical measure that reflects the quality of linearity. Its scale ranges from 0 to 1, where an R^2 equal to 1 indicates, in this context, that all data points fit perfectly to the linear regression. The regression resulted in an R^2 of 0.99517, indicating a good linear fit, with a variation of only 0.48% from the ideal linear fit.

As Fig. 6 demonstrates the isodose curves in relative values, the source center was set to 100% of the dose in the simulations to evaluate the percentage differences (PD) between the values obtained (Fig. 6) and the values simulated by the MCNP and TOPAS codes. The PD (%) between the results shown in Fig. 6 (E) and the simulated results were calculated using the MCNP (M) and TOPAS (T) results, with the values from Fig. 6 used as a reference, according to Equation (1). From these values, the mean relative percentage difference between the codes was also calculated.

$$PD(\%) = \frac{(M - E)}{E} * 100 \ \text{or} \quad PD(\%) = \frac{(T - E)}{E} * 100 \tag{1}$$

The FXG was moved to different positions to evaluate the variation in relative dose. Position determination was based on the graph obtained from a calibration performed on the Gammacell 220, which contains information about isodose curves provided by the institute itself. (Fig. 6). The dosimeter was positioned to replicate the relative values at different positions compared to the central dose.

The isodose curves in Fig. 6 follow a pattern proportional to the source's geometry. As they approach the source along the horizontal axis, the dose increases, while moving away from the center along the vertical axis results in a decrease in dose due to the absence of the source

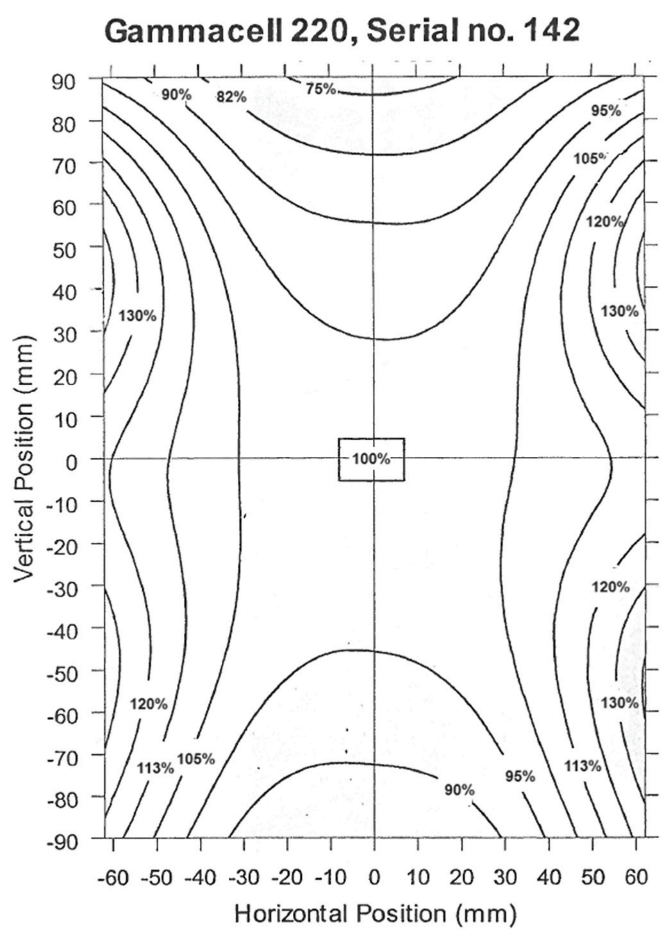

Fig. 6. Isodose curves measured in a plane passing through the Gammacell 220 symmetry axis conducted by an ionization chamber. Image provided by the institute itself.

at the vertical extremes, as illustrated in Fig. 1.

Table 2 showcases simulations that replicate the same behavior observed in the experimentally measured isodose curves. The simulated results demonstrated coherence compared to previous studies (Raisali and Sohrabpour, 1993; Rodrigues et al., 2010; Moradi et al., 2017; Aknouch et al., 2021).

The simulations between the two codes and the results based on Fig. 6 are consistent, with maximum differences of 18.65% for MCNP at 6 cm to the left of the center and 24.02% for TOPAS at 8 cm below the center. The minimum differences found are 1.26% for MCNP at 3 cm above the center and 1.80% for TOPAS at 3 cm to the left of the center. The smallest differences occur within displacements of up to 3 cm. As the target (FXG) moves further from the center, the differences increase because the simulations do not account for refractions and self-absorptions occurring in the experiments. This effect is due to the reduced contribution of scatter to the total dose at the edges of the simulator and should be considered when estimating the dose near the extremities of the object where the dose is deposited (Venselaar et al., 1996; Karaiskos et al., 1998). The mean relative percentage difference of 1.99% and 6.44% for the MCNP and TOPAS codes, respectively.

In all simulations, the maximum statistical uncertainties were up to 2% for MCNP and less than 7% for TOPAS. Considering that the GammaCell 220 is used as an irradiator in a nuclear institution, it is plausible to assert that MCNP is more comprehensive and applicable to this context.

It is important to emphasize that this study was based on a simplified geometry, modeling the source as an isotropic cylindrical shell with activity uniformly distributed along the cylinder. This simplified approach, although deviating from reality, yielded satisfactory results. Improvements could be achieved with a more detailed modeling, including specifying the activity of each rod and its position. However, due to the limitations of the study, which involved multiple reloads of the GammaCell 220 over decades, only the total activity of the source could be considered. Nevertheless, the remarkable agreement in the simulated results suggests the potential of this simplified simulation method.

Table 2
Simulated GammaCell 220 isodoses comparison with changes in the FXG position in MCNP e TOPAS.

	Simulated Deposited Energies (%)		Errors Associated to Energy (%)		Measured Deposited Energies (%)
Positions	MCNP	TOPAS	MCNP	TOPAS	Experimental
center	100.00	100.00	1.62	5.27	100.00
3 cm right horizontal	103.48	101.80	1.61	5.24	~100.00
5 cm right horizontal	124.36	107.97	1.50	5.03	105.00
3 cm left horizontal	106.00	106.17	1.59	5.07	~100.00
5 cm left horizontal	125.54	115.42	1.51	4.86	~113.00
6 cm left horizontal	142.37	126.48	1.45	4.60	~120.00
3 cm up vertical	93.81	81.49	1.75	5.80	~95.00
6 cm up vertical	87.16	77.89	1.84	5.97	~90.00
7 cm up vertical	82.43	78.41	1.92	6.01	90.00
8 cm up vertical	76.43	71.72	2.00	6.25	82.00
5 cm down vertical	91.50	83.55	1.79	5.79	~95.00
8 cm down vertical	78.87	68.38	1.98	6.33	90.00

4. Conclusion

The integration of simplified Monte Carlo modeling and experimental measurements using FXG enhances the understanding of the GammaCell 220 irradiator. The FXG dosimeter, employing a straightforward methodology, revealed a remarkable linear correlation between absorbance and absorbed dose, with an R^2 of 0.99517, indicating excellent linearity. Observed variations in absorbance at specific wavelengths were consistent with literature findings, validating the dosimeter's performance.

When comparing measured results with simulated ones, analyzing each position, it is observed that the MCNP code exhibits greater similarity compared to TOPAS. This observation aligns with the more versatile nature of MCNP, suitable for various nuclear applications, while TOPAS is typically preferred for radiation therapy simulations.

Acknowledging the study's limitations, the obtained results contribute to improving dose predictions and provide a valuable foundation for future advancements in computational modeling and experimental dosimetry.

Future advancements will include the implementation of other Monte Carlo codes that consider photon interactions and dispersion with greater precision, thereby increasing the accuracy of the simulations. Additionally, complementary studies involving the validation of simulated data with additional experimental measurements using other types of dosimeters could provide a more solid basis for comparing results. Future actions will also involve the validation of FXG for applications in radiotherapy.

Generative AI statement in scientific writing

During the preparation of this work, the authors used artificial intelligence tools to assist in the translation of this article. After use, the content was reviewed and edited, as necessary. The authors assume full responsibility for the content of the publication.

CRediT authorship contribution statement

P.S. Rodrigues: Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **A.L. Burin:** Writing – original draft, Validation, Software. **C.F. Talacimon:** Validation, Methodology. **I.M.M.A. Medeiros:** Conceptualization. **J.J.N. Pereira:** Software, Methodology, Conceptualization. **L.E.H. Teodoro:** Writing – original draft, Visualization. **M.E.Z. Rigo:** Visualization, Methodology. **M.M.F. Gesserame:** Conceptualization. **P.V.S. Tavares:** Software, Methodology, Data curation. **A.C. Martins:** Supervision. **C.D. Souza:** Writing – original draft, Supervision, Software, Conceptualization. **C.A. Zeituni:** Supervision. **O. Rodrigues:** Supervision, Software. **M.E.C.M. Rostelato:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

P. S. Rodrigues (01342.000815/2022-02), C. F. Talacimon (01342.000815/2022-02), P. V. S. Tavares (01341.000345/2022-89), M. E. Z. Rigo (01341.000164/2021-71) and M. M. F. Gesserame report financial support provided by National Nuclear Energy Commission. L. E. H. Teodoro (88887.689556/2022-00), I. M. M. A. Medeiros (88887.667254/2022-00) and J. J. N. Pereira (88887.704665/2022-00) report financial support provided by Coordination for the Improvement of Higher Education Personnel. A. L. Burin (140974/2023-7) reports financial support provided by National Council for Scientific and Technological Development.

Data availability

Data will be made available on request.

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References

Aknouch, A., El-ouardi, Y., Hamroud, L., Sebihi, R., Mouhib, M., Yjjou, M., Didi, A., Choukri, A., 2021. A Monte Carlo study to investigate the feasibility to use the Moroccan panoramic irradiator in sterile insect technique programs. Radiat. Environ. Biophys. 60, 673–679. https://doi.org/10.1007/s00411-021-00934-6.

Andreo, P., 1991. Monte Carlo techniques in medical radiation physics. Phys. Med. Biol. 36, 861–920. https://doi.org/10.1088/0031-9155/36/7/001.

Andreo, P., 2018. Monte Carlo simulations in radiotherapy dosimetry. Radiat. Oncol. 13 https://doi.org/10.1186/s13014-018-1065-3.

ATOMIC ENERGY OF CANADA LIMITED (AECL), 1974. Specification of Gammacell 220 Irradiation Unit. Number JS-300. Ottawa: COMMERCIAL PRODUCTS.

Austerlitz, C., Mota, H., Almeida, C.E., Allison, R., Sibata, C., 2007. Quality assurance of HDR sources using a Fricke dosimeter. Med. Phys. 34, 1348–1353. https://doi.org/10.1118/1.2714472.

Briesmeister, J.F., 2000. MCNPTM-A General Monte Carlo N-Particle Transport Code. Version 4C, LA-13709-M, 2. Los Alamos National Laboratory.

Chan, M.F., Ayyangar, K., 1995. Verification of water equivalence of FeMRI gels using Monte Carlo simulation. Med. Phys. 22, 475–478. https://doi.org/10.1118/1.597540.

Del Lama, L.S., de Góes, E.G., Petchevist, P.C.D., Moretto, E.L., Borges, J.C., Covas, D.T., de Almeida, A., 2013. Prevention of transfusion-associated graft-versus-host disease by irradiation: technical aspect of a new ferrous sulphate dosimetric system. PLoS One 8, e65334. https://doi.org/10.1371/journal.pone.0065334.

Fricke, H., Morse, S., 1927. The chemical action of roentgen rays on dilute ferrosulphate solutions as a measure of dose. Am. J. Roentgenol. Radium Ther. Nucl. Med. 18, 430–432.

Gupta, B.L., Bhat, R.M., Narayan, G.R., Nilekani, S.R., 1985. A spectrophotometric readout method for free radical dosimetry. Radiat. Phys. Chem. 26, 647–656. https://doi.org/10.1016/0146-5724(85)90102-5.

Karaiskos, P., Angelopoulos, A., Sakelliou, L., Sandilos, P., Antypas, C., Vlachos, L., Koutsouveli, E., 1998. Monte Carlo and TLD dosimetry of an high dose-rate brachytherapy source. Med. Phys. 25 (10), 1975–1984. https://doi.org/10.1118/1.598371.

Knoll, I.M., Quevedo, A., Sánchez, M.S.A., 2022. Applications of simulation codes based on Monte Carlo method for radiotherapy. In: The Monte Carlo Methods - Recent Advances, New Perspectives and Applications. IntechOpen. https://doi.org/10.5772/intechopen.101323.

Liosi, G.M., Dondi, D., Vander Griend, D.A., Lazzaroni, S., D'Agostino, G., Mariani, M., 2017. Fricke-gel dosimeter: overview of Xylenol Orange chemical behavior. Radiat. Phys. Chem. 140, 74–77. https://doi.org/10.1016/j.radphyschem.2017.01.012.

Moradi, F., Khandaker, M.U., Mahdiraji, G.A., Ung, N.M., Bradley, D.A., 2017. Dose mapping inside a gamma irradiator measured with doped silica fibre dosimetry and Monte Carlo simulation. Radiat. Phys. Chem. 140, 107–111. https://doi.org/10.1016/j.radphyschem.2017.01.032.

Otomo, M., 1965. Composition of the Xylenol Orange complexes of iron (III) and their application to the determination of iron or Xylenol Orange. Bunseki Kagaku 14, 677–682. https://doi.org/10.2116/bunsekikagaku.14.677.

PACIFIC NORTHWEST NATIONAL LABORATORY (PNNL), 2021. Data Mining Analysis and Modeling Cell Compendium of Material Composition Data for Radiation Transport Modeling. United States Department of Energy, Alexandria.

Perl, J., Shin, J., Schümann, J., Faddegon, B., Paganetti, H., 2012. TOPAS: an innovative proton Monte Carlo platform for research and clinical applications. Med. Phys. 39, 6818–6837. https://doi.org/10.1118/1.4758060.

Raisali, G.R., Sohrabpour, M., 1993. Application of egs4 computer code for determination of gamma ray spectrum and dose rate distribution in gammacell 220. Radiat. Phys. Chem. 42, 799–805. https://doi.org/10.1016/0969-806x(93)90376-6.

Rodrigues, R.R., Grynberg, S.E., Ferreira, A.V., Belo, L.C.M., Squair, P.L., Sousa, R.V., Sebastião, R.C.O., Ribeiro, M.A., 2010. Retrieval of GammaCell 220 irradiator isodose curves with MCNP simulations and experimental measurements. Braz. J. Phys. 40, 120–124. https://doi.org/10.1590/s0103-97332010000100017.

Schreiner, L.J., 2015. True 3D chemical dosimetry (gels, plastics): development and clinical role. J. Phys. Conf. 573, 012003 https://doi.org/10.1088/1742-6596/573/1/012003.

Uzorka, A., Bale, J., Kibirige, D., 2022. Preliminary study on the use of Fricke gel dosimeter for verification of IMRT beam delivery. Biophys. Rev. Lett. 17, 87–105. https://doi.org/10.1142/s1793048022500059.

Venselaar, J.L.M., Van der Giessen, P.H., Dries, W.J.F., 1996. Measurement and calculation of the dose at large distances from brachytherapy sources: Cs-137, Ir-192, and Co-60. Med. Phys. 23 (4), 537–543. https://doi.org/10.1118/1.597811.

Yan, H., Wu, X., Yang, J., 2015. Application of Monte Carlo method in tolerance analysis. Proc. CIRP 27, 281–285. https://doi.org/10.1016/j.procir.2015.04.079.