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Computational Modeling of The Brazilian Army Gamma Calibration Laboratory Using the MCNP Transport Code

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Abstract: The Brazilian Army's responsibility for nuclear defense operations, as defined in the National Defense Policy and Army Strategic Plan, has led to advancements in this field, as the establishment of the Gamma Monitor Calibration Laboratory (LCG) at the Institute of Chemical, Biological, Radiological, and Nuclear Defense (IDQBRN) within the Brazilian Army Technology Center (CTEx). The LCG calibrates radiation monitors for troops in defense operations and emergencies. It has secured accreditation from the Evaluation Committee for Testing and Calibration Services (CASEC) and is currently seeking certification from the National Institute of Metrology, Standardization, and Industrial Quality (INMETRO) to enhance its Cs-137 calibration capabilities for radiological protection. All activities must adhere to relevant ABNT NBR standards. The primary aim of this paper is to develop a computational model of the LCG that integrates the irradiation system, utilizing the Monte Carlo N-Particle (MCNP) radiation transport code. This model will initially be employed to evaluate backscattered radiation and will remain available for future applications and testing. This simulation was performed using MCNP5, and the graphical input file editor (VISED) was used to verify the defined geometry. The modeling was based on construction data and the specifications of the internal equipment. The input file was created and utilized in the code, providing the output file with the ambient dose equivalent normalized per photon emitted at the source. Then, the result was adjusted for source activities and converted into a dose rate. All simulated values were lower than the experimental ones, for example, for the condition without attenuation at 1 m, the simulated value is 3,0816 mSv/h, while the experimental is 3,1930 mSv/h.

Keywords: Gamma Radiation, Calibration, Ambient Dose Equivalent, Monte Carlo Simulation.

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Modelagem Computacional do Laboratório de Calibração de Monitores Gama do Exército Brasileiro Usando o Código MCNP

Resumo: A responsabilidade do Exército Brasileiro pelas operações de defesa nuclear, conforme definido na Política Nacional de Defesa e no Plano Estratégico do Exército, levou a avanços neste campo, como o estabelecimento do Laboratório de Calibração de Monitores Gama (LCG) no Instituto de Defesa Química, Biológica, Radiológica e Nuclear (IDQBRN) dentro do Centro Tecnológico do Exército Brasileiro (CTEx). O LCG calibra monitores de radiação para tropas em operações de defesa e emergências. Ele garantiu a acreditação pelo Comitê de Avaliação de Serviços de Ensaios e Calibração (CASEC) e está atualmente buscando a certificação do Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (INMETRO) para aprimorar suas capacidades de calibração no campo do Cs-137 para proteção radiológica. Todas as atividades devem aderir aos padrões ABNT NBR relevantes. O objetivo principal deste artigo é desenvolver um modelo computacional do LCG que integra o sistema de irradiação, utilizando o código de transporte de radiação Monte Carlo N-Particle (MCNP). Este modelo será inicialmente empregado para avaliar a radiação espalhada e permanecerá disponível para futuras aplicações e testes. Esta simulação foi realizada usando o MCNP5, o editor de arquivos de entrada gráfico (VISED) foi usado para verificar a geometria definida. A modelagem foi baseada em dados de construção e nas especificações dos equipamentos internos. O arquivo de entrada foi criado e utilizado no código, fornecendo o arquivo de saída com a dose ambiente equivalente normalizada por fóton emitido na fonte. Em seguida, o resultado foi ajustado para as atividades da fonte e convertido em uma taxa de dose. Todos os valores simulados foram menores que os experimentais, por exemplo, para a condição sem atenuação a 1 m, o valor simulado é 3,0816 mSv/h, enquanto o experimental é 3,1930 mSv/h.

Palavras-chave: Radiação Gama, Calibração, Equivalente de Dose Ambiente, Simulação em Monte Carlo.

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1. INTRODUCTION

The LCG was established in 2015 to meet the demand for calibrating the radiological monitoring equipment used by the troops [1]. This responsibility within the scope of national defense has been assigned to the Brazilian Army as one of its missions, promoting technical and scientific development. The Armed Forces must be prepared to handle risky situations, such as accidents and emergencies of all scales. However, dealing with radiation is fundamental to ensure the quality of field measurement, and defining the damage associated with that interaction. For this, the radiation monitors must be calibrated according to the standards set by the regulatory authority [2].

The laboratory has an IG-13 irradiator (VF Nuclear) containing two sealed sources (Cs-137 and Co-60) in a remote-controlled automatic carousel. Despite that, this study aims to validate the modeling only for Cs-137. This isotope is typically the standard for calibration in this laboratory due to its monoenergetic behavior, reproducibility of results, and longer half-life compared to Co-60. The positioning of the radiation monitors to be calibrated varies in x, y, and z coordinates, defined by lasers. The purpose of this system is to calibrate area radiation monitors for use in radiological protection. The operational quantity ambient dose equivalent rate ($\dot{H}^*(10)$) is the standard for calibration laboratories [1]. Currently, the LCG is certified by the CASEC/CNEN. However, it is still working towards accreditation with the INMETRO to qualify for inclusion in the Brazilian Calibration Network (RBC/INMETRO). These bodies are national authorities that regulate and authorize the provision of that service. They are part of a hierarchical structure under international organizations that promote technical cooperation and standardization of the unit system. The International Bureau of Weights and Measures (BIPM) maintains the International

Measurement System (SI) defined at the Metre Convention, which allows the comparison of values in a standardized global system [3].

The approval of laboratories by these bodies is assured by complying with relevant national standards, such as the ABNT NBR ISO/IEC 17025:2017 [4] and ABNT NBR ISO 4037:1-3 [5, 6, 7]. These standards specify critical aspects that must be understood and respected within the calibration environment, including physical and nuclear phenomena. While one method of studying these concepts is through experimental activities, computational simulations are increasingly being utilized to model the interactions of radiation with matter.

The MCNP transport radiation code is based on the Monte Carlo Method (MCM). In the nuclear and radiological sectors, the MCM has enabled the development of a code capable of generating many types of radiation and particles, including elementary particles. The simulated environment can show significant complexity across all code functionalities. The tally obtained in the simulation is a user-defined marker calculated at the output, where each value calculated is associated with a statistically estimated relative error. Once the physical quantity is obtained through simulation (tally), tabulated conversions can result in a dosimetric, limiting, or operational quantity [8].

The International Commission on Radiological Protection (ICRP) publishes recommendations and guides on several topics related to the radiological protection of people, animals, and the environment. Here, the ICRP 74 was used to convert the normalized gamma flux at a point detector calculated by the code to a normalized dose [9]. Subsequently, the dose rates were adjusted based on the source activities recorded on the dates of the experimental measurements. The experimental values obtained earlier were used to validate the simulated results.

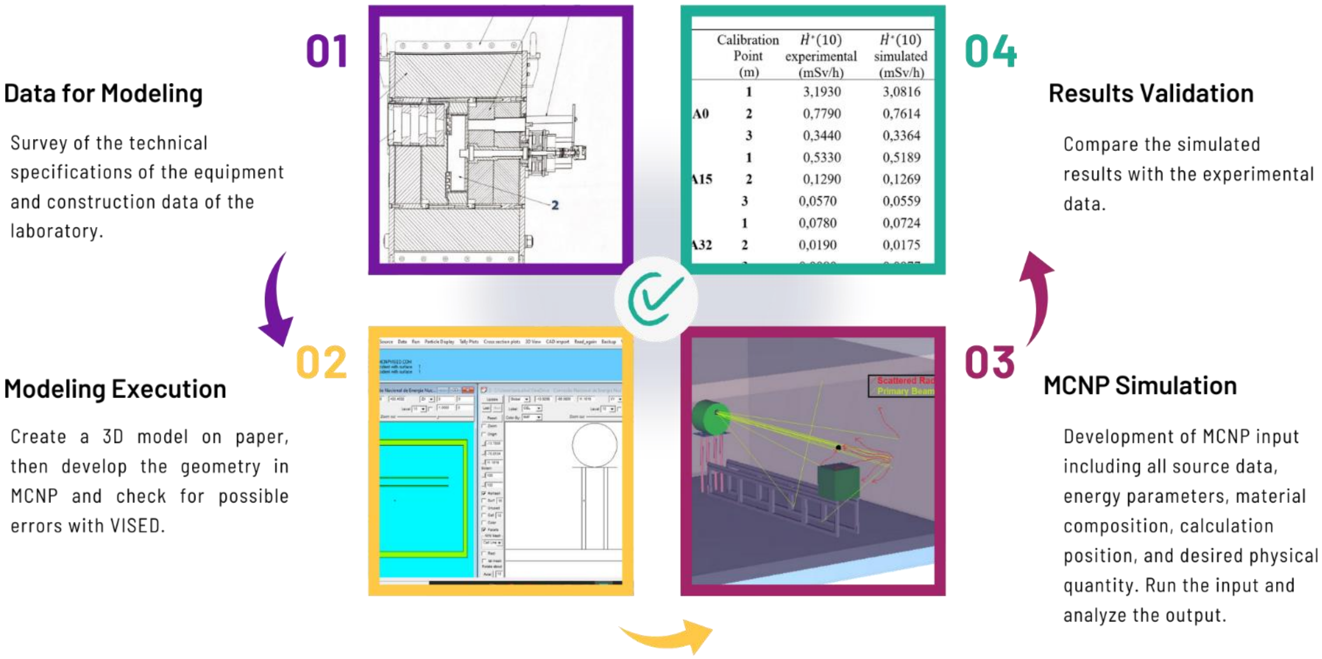
Thus, the goal of this study is to develop a computational model for the LCG using MCNP simulation. This modeling will support future research, whether for certification purposes or operational routines.

The scientific foundation was established through research conducted at the Radiation Protection Laboratory of the Ezeiza Atomic Center (CAE), which is part of the National Atomic Energy Commission (CNEA), and at the Calibration Laboratory of the Institute of Energy and Nuclear Research (IPEN/CNEN) [10, 11]. These laboratories performed comprehensive dosimetric studies that included both theoretical and practical parameters. A similar study was previously conducted for the LCG as part of a master's thesis, providing experimental values that were used to validate the data from this simulation [12]. Both studies employed MCNP simulations to assess the contribution of scattered radiation to the measurements, either independently or by comparing it with other methods. The model developed in this work can also be utilized to evaluate this contributing percentage at LCG. However, this literature does not validate the data with experimental measurements. According to other works that followed this approach, the expected relative errors between the simulated and experimental values are around 5-6% [13, 14].

2. MATERIALS AND METHODS

This project was divided into four main stages. The first two stages involved gathering data to model the LCG, where all technical specifications were collected, and any missing information was estimated using proportional methods. The latter stages focused on simulating the executed model, during which the desired quantities were calculated and analyzed. The output results were compiled into a self-authoring table that corrected the source activity and converted the normalized dose into a dose rate. The Visual Editor for MCNP input (VISED) was used to verify the geometry before and after running the code. Figure 1 illustrates the evolution of this research. A previous dosimetric study of this laboratory provided the Cs-137 dose rates used in this document for validation purposes [12].

Figure 1: Diagram Flow of the LCG Modeling Process.



Source: Author.

2.1. The Laboratory

LCG was constructed at the Army Technological Center (CTEx) under the operational command of the IDQBRN. The wall that receives the primary beam has 30 cm thick concrete at the facility's back. All other walls, including those of the antechamber preceding the laboratory, are 30 cm thick and made of barite mortar. These construction features directly relate to the radiation shielding condition of the two sealed sources inside the irradiator. The background radiation when the sources are at their irradiating position is 0,20 μSv/h in the external area of the laboratory, while it is 0,28 μSv/h inside the antechamber, measured in terms of personal dose equivalent. ($\dot{H}$p (10)) [1].

This space is equipped with instruments calibrated by qualified authorities to ensure accuracy of measurements. Throughout the calibration process, climatic conditions are continuously monitored, allowing for necessary adjustments. The measurement system used for assessing the air kerma rate consists of a 1 L ionization chamber from PTW (model: TW32002, serial number: 528) and a PTW UNIDOS electrometer (model: Webline, serial number: T10022-999452), both of which were calibrated at the National Laboratory for Ionizing Radiation Metrology (LNMRI). This system detects and measures the electric charge generated by the ionization of atoms in the active control volume. The average electric current is then calculated and converted into the air kerma rate using an air kerma calibration factor (NK) of 2.4987E+04 (Gy/C), which has an uncertainty of 2.6%, as stated in the calibration certificate. Subsequently, this air kerma rate is converted into an equivalent ambient dose rate using the conversion coefficients outlined in ABNT NBR ISO 4037-3 [7], as the ambient dose equivalent is the operational radiological quantity commonly used in calibration laboratories for area monitors. The operational data acquisition points are located at intervals of 0.5 meters between 0.5 and 3 meters from the center of the source. However, point detectors were placed at 1 meter, 2 meters, and 3 meters for the simulation of the ambient dose equivalent discussed in this article.

The calibration events at the LCG are controlled remotely from the operational room next to the antechamber for safety. Two computers handle remote access in the control room. One is connected to the climate monitoring system, while the other provides real-time visualization of the internal cameras and operates the irradiator. All the equipment involved in this activity is listed in Table 1. The irradiator and all its internal components were purchased as a complete unit.

Table 1: Equipment for Gamma Calibration of Area Radiation Monitors at LCG.

DEVICE	CHARACTERISTICS
Gamma irradiator	Model IG-13, Manufactured by VF Nuclear
Cs-137 Source	Cs.P04 Model, Manufactured by Eckert & Ziegler; Initial Activity of 36.9 GBq (January 22, 2015)
Co-60 Source	COS-15HH Model, Manufactured by Eckert & Ziegler; Initial Activity of 36 GBq (March 24, 2015)
1 L ionization chamber detectors	Two Units: Model TW32002, Manufactured by PTW Unidos; cavity chamber type
Electrometers	Two Units: Model Webline, Manufactured by PTW Unidos
Laser	3D Positioning System
Calibration Bench and Table	Manufactured by PTW Calibration Bench
Climatic Conditions System	Includes a Thermometer (0,1 ºC), a Barometer (0,1 hPa), a Hygrometer (1%), an Air Dehumidifier, and an Air Conditioning

2.2. MCNP – Modeling and Simulation

The code version used here was MCNP5, belonging to the Nuclear Engineering Section of the Military Institute of Engineering (SE7/IME). The computers used to run the simulations have identical specifications. They are manufactured by Positivo Tecnologia S.A. and are equipped with an AMD Ryzen 5 PRO 4650GE with Radeon Graphics processor running at 3.30 GHz. Each computer has 16 GB of installed RAM, of which 15.4 GB is usable. The operating system is 64-bit Windows 11 Pro. In this study, all inputs were processed using 7 cores. The computer times for each scenario are as follows: without attenuation took 15,008.18 minutes; with 15 mm attenuation, it took 13,532.47 minutes; and with 32 mm attenuation, it took 15,197.27 minutes.

The determination of the operational quantity differed from the procedures established in the laboratory's calibration protocols. The point detector tally (F5) calculated the photon flux per unit area and normalized it per photon emitted at the source.

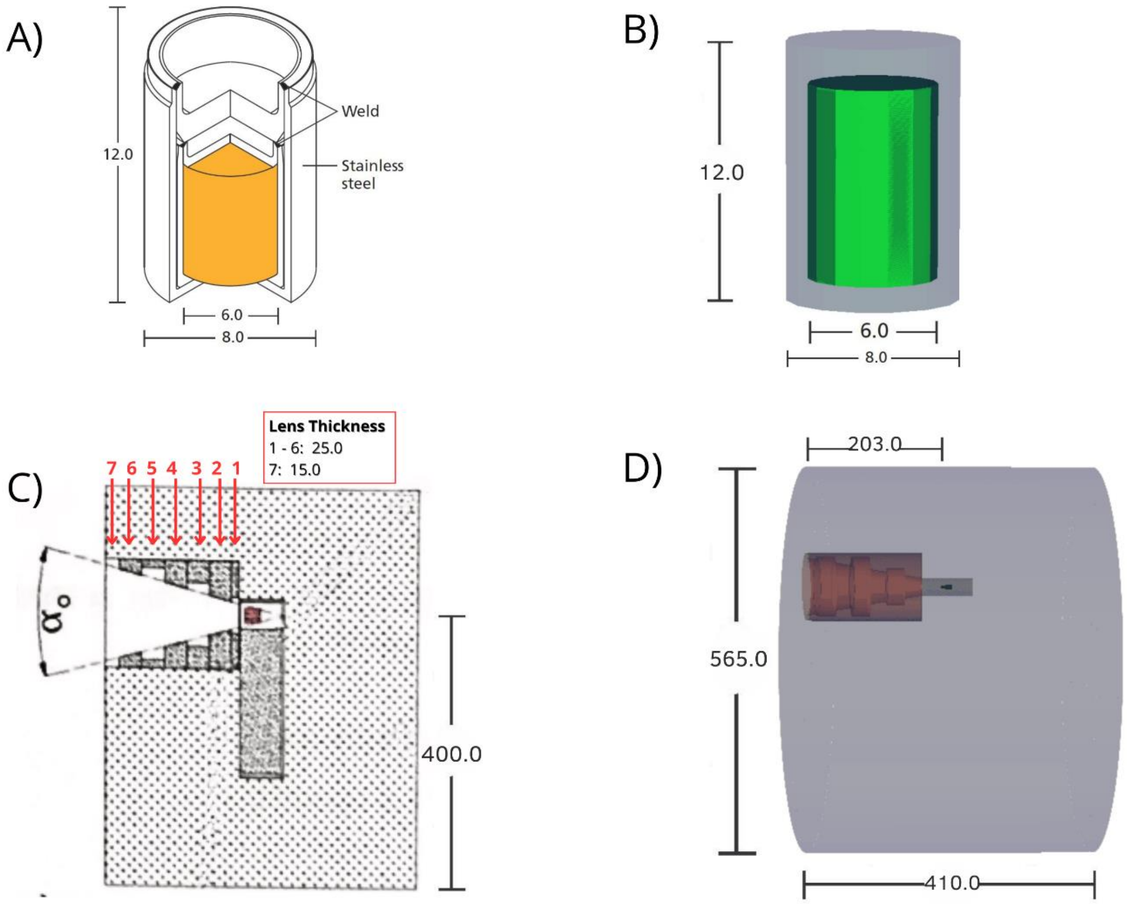
Using the Dose Energy (DE)/Dose Function (DF) card on the input, each flux tally was converted to an ambient dose equivalent using the conversion factors from ICRP 74 [7]. At this point, the dose rate was corrected for the source activity on the day of the experimental data acquisition. The comparison with laboratory data allowed the validation of this model.

The cylindrical pellet, composed of ceramic material, is encased in a double-layer stainless steel encapsulation. The initial activity in January 2015 was 36.9 GBq. Its positioning within the carousel is horizontal with a slight inclination, which is not represented in this modeling.

The primary beam is emitted at an angle of 10° with the horizontal when the source is in the irradiation position, passing through the tungsten annular collimator. The maximum angle of beam dispersion after the collimator forms a cone with an apex angle of 20 degrees. All these structures are internal to the lead irradiator. The central line of the primary beam is located at 1,45 m from the ground. Figure 2 shows some details.

The decay of Cs-137 primarily occurs through beta emission, resulting in gamma radiation. About 95% of the nuclear transitions lead to Barium-137 on the metastable state (Ba-137m). This excess energy is released through photons with an energy of 0.662 MeV at 85 emissions per 100 disintegrations. The remaining 5% of disintegrations occur with the emission of only more energetic beta particles directly to the stable state of B-137a [16]. To ensure consistency with the validation experimental study, the decay considered in the input is 100% gamma radiation of this characteristic energy.

Figure 2: Components of the irradiator. A) The design of the source was derived from the manufacturer's technical specifications, detailing the active length of the cesium ceramic core and the dual 316L stainless-steel encapsulation. B) 3D visualization of the simulation source was created in VISED, showcasing a cesium nitrate core with dual 316L stainless-steel encapsulation. C) The cross-section of the lead alloy irradiator includes a detailed view of the tungsten alloy annular collimator, featuring α = 20º irradiation angle as outlined in the manufacturer's technical documentation. D) 3D visualization of both the pure lead irradiator and the pure tungsten annular collimator was generated in VISED. All dimensions are in millimeters.



Source: Author and Sealed Radiation Sources by Eckert & Ziegler Nuclitec [15].

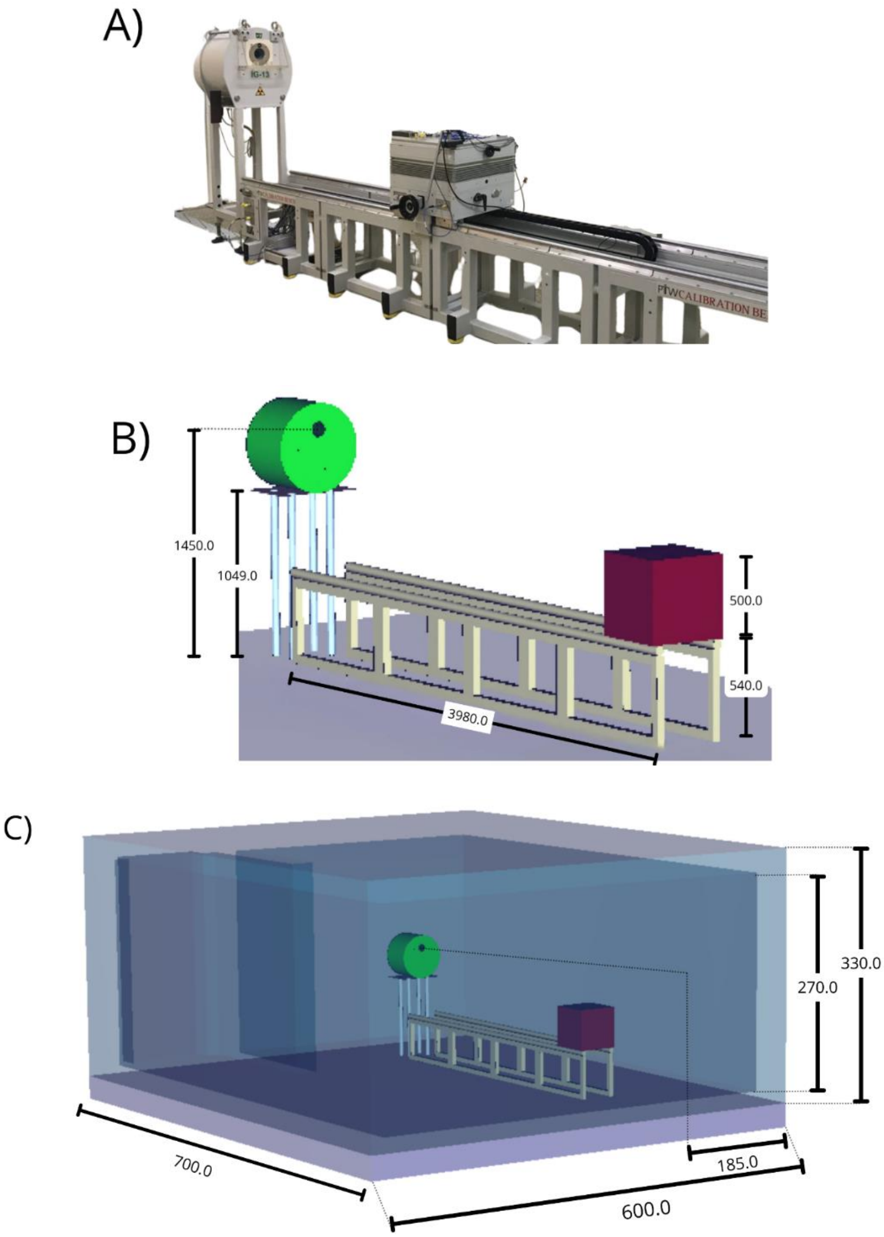
The material compositions were sourced from the Compendium of Material Composition Data for Radiation Transport Modeling, Rev. 1 (2011) (PIET-43741-TM-963, PNNL-15870 Rev. 1 [17], compiled by the Pacific Northwest National Laboratory for the United States Department of Energy. The materials used in the simulation include pure lead, pure tungsten, 316L stainless steel, barite concrete, pure iron, cesium nitrate, and typical western soil. The composition of 50% humid air is as follows: 1000 0.0005818 6000 0.0001234 7000 0.7513406 8000 0.2351939 18000 0.0127603.

The spatial variation of the calibrated detector is achieved through the bench and calibration table system positioned immediately in front of the irradiator. This system facilitates movement along the three Cartesian axes and defines its position using lasers. The bench is 4 meters long and ends near the wall that receives the primary beam. While the bench has been modeled as solid, the calibration table is hollow since it houses the internal electrical movement systems. Both items are made from stainless steel 316L.

A pair of lead attenuators is used to vary the dose rate from 10 μSv/h to 1 mSv/h at the specified distance. The first attenuator is 15 mm thick, and the second is 32 mm thick, both with rectangular geometry (200 mm x 100 mm). These attenuators are placed one at a time at the collimator's output, covering its entire opening. An acrylic support is attached to the irradiator to hold the attenuator plate. For each attenuation condition, dose rates are calculated at the specified positions mentioned above.

It is possible to visually compare the laboratory with the proposed modeling in Figure 3. For this study, only the direct irradiation system, which includes the irradiator, calibration table, and bench, was modeled. The climate control systems, ionization chamber for internal dosimetry, lasers, and electrometers were excluded from the representation. The walls and floor are shown according to their construction characteristics and materials.

Figure 3: Comparison of the Laboratory with the Modeling in Vised. A) A photo showcasing the interior of the LCG, highlighting the irradiator system, the calibration bench, and the table made from 316L stainless steel. It also features the irradiator feet, which are made of an iron alloy. B) A 3D visualization generated in VISED, depicting the previous system composed of 316L stainless steel and irradiator feet made of pure iron. C) A 3D view presenting the complete geometry of the LCG, including walls, ceiling, and floor made of barite concrete, along with typical western soil. All dimensions are in millimeters.



Source: Author.

3. RESULTS AND DISCUSSIONS

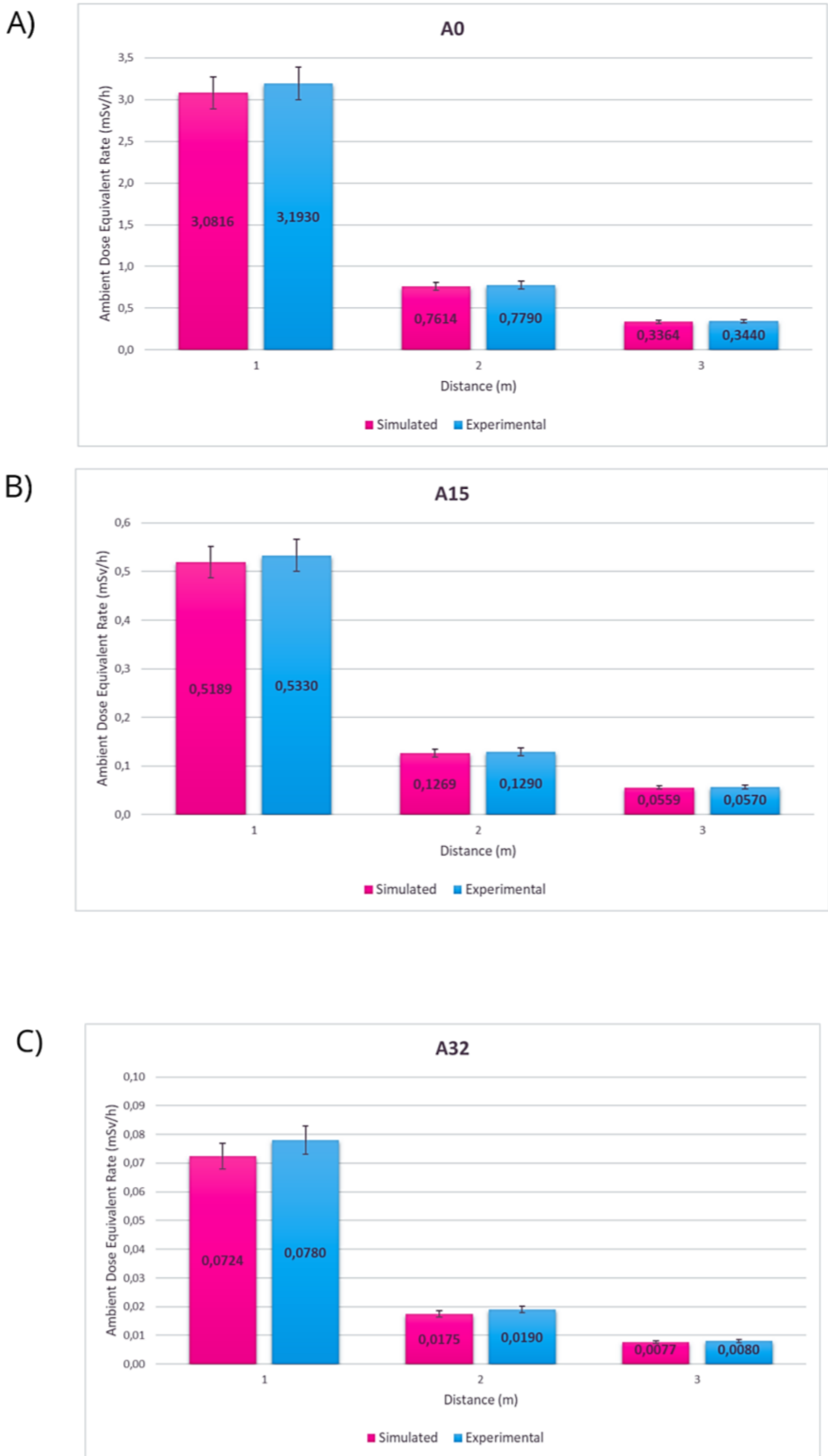
The executed inputs were simulated under three attenuation conditions: no attenuation (A0), attenuation with a 15 mm plate (A15), and attenuation with a 32 mm plate (A32). The cutoff parameter was the number of photons initiated at the source (NPS) on the order of 10^9. It was verified that for this NPS, the relative errors associated with the tallies were reasonably below the confidence limit. According to the code manual [8], errors below 5% are generally reliable for point detector flux tallies. The code understands the relative error associated with the calculated tally as the ratio between the standard deviation of the mean and the estimated mean [8]. The simulation results are presented in Table 2.

Table 2: Simulation of the Operational Quantity in Ambient Dose Equivalent Rate for the LCG.

ATTENUATION CONDITION	DISTANCE FROM THE SOURCE (m)	SIMULATED DOSE RATE (mSv/h)	MCNP RELATIVE ERROR
A0	1	3,0816	0,0001
	2	0,7614	0,0001
	3	0,3364	0,0002
A15	1	0,5189	0,0005
	2	0,1269	0,0005
	3	0,0559	0,0005
A32	1	0,0724	0,0014
	2	0,0175	0,0013
	3	0,0077	0,0013

The simulated values obtained are consistent; as the attenuation condition increases, the dose rates decrease. Furthermore, the attenuators performed their role in achieving the expected order-of-magnitude variation in these rates. It is also observed that, for the same attenuation, dose rates decrease with increasing distance. This characteristic aligns with the expected behavior of radiation intensity according to the inverse square law.

Figure 4: Validation of the LCG Modeling through the Comparison between Experimental and Simulated Dose Rates. A) No attenuation condition. B) 15 mm attenuation condition. C) 32 mm attenuation condition.



Source: Author.

Figure 4 provides a comparative graphical representation between the laboratory dose rate values and the simulated ones for all attenuation conditions. Introducing the experimental data alongside the simulation results demonstrated the accuracy achieved with this modeling. In this study, we define the true value of the measurement dose rate as the experimental data obtained from the laboratory's internal dosimetry, which ensures depth traceability [18]. The maximum relative errors of the simulated data are as follows: it is below 4% for the condition without attenuation, below 3% for the condition with average attenuation, and below 9% for the condition with the highest attenuation. The values for the first two conditions align with the dispersion typically observed in MCNP simulation studies [13, 14]. However, in the last condition, the code demonstrates poor performance, with dose rates on the order of 10 μSv. This could be attributed to several factors, including the sensitivity of the tally used, the conversion factors applied in this low-energy range, or increased scattering in this condition.

Another observation from these graphs is the apparent presence of a measurement bias that introduces a systematic error, as the simulated values are consistently lower than the experimental values across all calibration points and attenuation levels. This factor can be attributed to the necessary simplifications imposed on the model's geometry for the reasons discussed earlier. The authors believe that with greater detail, the relative errors are likely to decrease.

A recent study calculated the measurement uncertainties in terms of ambient dose equivalent rate for LCG dosimetry and for the LCG radiation monitors calibration [19]. The analysis included both the combined standard uncertainty and the expanded uncertainty, assuming a normal distribution with a coverage factor of k = 2.0. The study compiled all necessary data to assess Type A and Type B measurement uncertainties, ultimately estimating the maximum expanded uncertainty for laboratory dosimetry to be 6.2%. Since the development of the simulation did not account for uncertainty propagation due to a lack of available data at the time, the same expanded uncertainty value will be applied to the simulated data. As a result, the error bars in Figure 4 represent the expanded uncertainty value determined in the referenced study.

4. CONCLUSIONS

This work executed and presented the MCNP modeling developed based on the technical specifications and construction characteristics of the Brazilian Army's gamma calibration laboratory (LCG). Additionally, the study utilized pre-existing dosimetry data from this laboratory to validate the proposed modeling.

The high number of histories generated in the code resulted in small relative errors in the calculation of each tally when compared to the threshold values provided in the manual. This work is highly important for the laboratory and was completed within a short time frame. However, the results underscored the need for more detailed input to minimize relative errors in cases of maximum attenuation. Under the other two conditions, the simulation performed as expected, with relative errors consistent with those reported in the literature.

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CONFLICT OF INTEREST

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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