



Original Article

Low-Dose Gamma Radiation Dosimetry Using a ^{60}Co Irradiator: Experimental Validation and Reproducibility

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Abstract: Low-dose ionizing radiation has been increasingly investigated in preclinical research due to its potential to modulate biological responses while minimizing the risk of significant tissue damage. However, the scientific reliability of studies conducted in the milliGray dose range strongly depends on the availability of rigorous, reproducible, and traceable dosimetric protocols. Small variations in irradiation geometry, exposure time, or shielding conditions may result in substantial uncertainties when low doses are involved, reinforcing the importance of precise dosimetric characterization and standardized experimental methodologies. In this context, the present study describes the development and validation of a low-dose gamma radiation dosimetry protocol (~41.3 mGy) implemented using a multipurpose cobalt-60 (^{60}Co) irradiator at the Gamma Irradiation Laboratory (LIG) of the Nuclear Technology Development Center (CDTN), Brazil. The protocol was designed to support preclinical experiments, with emphasis on accuracy, reproducibility, and strict compliance with radiological protection requirements. Dosimetric planning was based on the Beer–Lambert exponential attenuation law, applied to the dimensioning of lead shielding and to the definition of the transmitted beam fraction required to achieve the target dose. These theoretical calculations were integrated with the geometric configuration of the irradiation system, including source-to-sample distance and exposure time, to ensure controlled dose delivery within the milliGray range. A conservative experimental configuration was adopted, employing the maximum operational distance available in the irradiator to reduce dose rates and improve temporal control during short irradiation times. Lead shielding elements were used to stabilize the irradiation setup and to ensure consistent attenuation of the gamma beam. All irradiation



procedures followed the routine operational practices of the LIG/CDTN, ensuring dosimetric traceability and adherence to national radiological protection standards. The results demonstrate that the proposed protocol enables the controlled and reproducible delivery of low gamma doses with suitable radiation field uniformity for preclinical applications. Overall, the methodology provides a robust and adaptable dosimetric framework for experimental studies requiring low-dose gamma irradiation, contributing to improved standardization, safety, and comparability in preclinical dosimetry research.

Keywords: Dosimetry, gamma radiation, low-dose irradiation, cobalt-60.



Dosimetria de Radiação Gama de Baixa Dose Usando um Irradiador de ^{60}Co : Validação Experimental e Reprodutibilidade

Resumo: A radiação ionizante de baixa dose tem sido cada vez mais investigada em pesquisas pré-clínicas devido ao seu potencial de modular respostas biológicas, minimizando o risco de danos teciduais significativos. Entretanto, a confiabilidade científica de estudos conduzidos na faixa de dose de miliGray depende fortemente da disponibilidade de protocolos dosimétricos rigorosos, reprodutíveis e rastreáveis. Pequenas variações na geometria de irradiação, no tempo de exposição ou nas condições de blindagem podem resultar em incertezas substanciais quando baixas doses estão envolvidas, reforçando a importância de uma caracterização dosimétrica precisa e de metodologias experimentais padronizadas. Nesse contexto, o presente estudo descreve o desenvolvimento e a validação de um protocolo de dosimetria de radiação gama de baixa dose ($\sim 41,3$ mGy), implementado utilizando um irradiador multipropósito de cobalto-60 (^{60}Co) no Laboratório de Irradiação Gama (LIG) do Centro de Desenvolvimento da Tecnologia Nuclear (CDTN), Brasil. O protocolo foi concebido para dar suporte a experimentos pré-clínicos, com ênfase em precisão, reprodutibilidade e conformidade com os requisitos de proteção radiológica. O planejamento dosimétrico foi fundamentado na lei de atenuação exponencial de Beer-Lambert, aplicada ao dimensionamento da blindagem de chumbo e à definição da fração transmitida do feixe necessária para atingir a dose-alvo. Esses cálculos teóricos foram integrados à configuração geométrica do sistema de irradiação, incluindo a distância fonte-amostra e o tempo de exposição, de modo a garantir a entrega controlada da dose na faixa de miliGray. Foi adotada uma configuração experimental conservadora, utilizando a maior distância operacional disponível no irradiador, com o objetivo de reduzir as taxas de dose e melhorar o controle durante curtos tempos de irradiação. Elementos de blindagem em chumbo foram empregados para estabilizar o arranjo experimental e assegurar a atenuação consistente do feixe gama. Todos os procedimentos seguiram as práticas operacionais rotineiras do LIG/CDTN, garantindo rastreabilidade dosimétrica e conformidade com as normas nacionais de proteção radiológica. Os resultados indicam que o protocolo proposto permite a entrega controlada e reprodutível de baixas doses de radiação gama, com adequada uniformidade do campo de radiação para aplicações pré-clínicas. Dessa forma, a metodologia estabelece uma referência dosimétrica robusta, passível de adaptação a outros arranjos experimentais que demandem irradiação gama de baixa dose.

Palavras-chave: Dosimetria, radiação gama, irradiação de baixa dose, cobalto-60.

1. INTRODUCTION

Low-dose ionizing radiation (LDIR) has gained increasing attention in preclinical research due to its potential to modulate biological and cellular responses while avoiding the deterministic tissue damage typically associated with higher absorbed doses. In the milliGray dose range, experimental observations have suggested subtle but measurable effects on inflammatory signaling, oxidative balance, and cellular stress responses, particularly in controlled *in vivo* and *ex vivo* models [1,2]. However, the scientific reliability of these studies critically depends on accurate dosimetric characterization, since small deviations in delivered dose may represent a significant fraction of the intended exposure.

Unlike irradiation protocols operating in the Gray range, low-dose experiments are especially sensitive to uncertainties related to irradiation geometry, exposure time, source positioning, shielding configuration, and scattered radiation. Variations of only a few seconds in exposure time or minor geometric misalignments can lead to substantial relative errors when doses on the order of tens of milliGray are prescribed. Consequently, reproducible, traceable, and well-documented dosimetric protocols are a methodological prerequisite for preclinical LDIR investigations [3,4].

Gamma irradiators based on sealed cobalt-60 (^{60}Co) sources remain widely employed in research facilities due to their operational stability, long half-life, and well-defined photon energies (1.17 and 1.33 MeV). These characteristics make ^{60}Co irradiators suitable for standardized irradiation procedures; however, achieving low absorbed doses requires careful control of distance, exposure time, and attenuation conditions, particularly in multipurpose irradiation facilities [5]. In such environments, dose rate strongly depends on the source-to-sample distance and may be influenced by facility-specific scattering and buildup effects.

The physical basis for attenuation-based dose control in gamma fields is commonly described by the Beer–Lambert exponential attenuation law, which relates transmitted

intensity to the linear attenuation coefficient of the shielding material and its thickness. This formalism has been extensively applied in recent studies addressing gamma-ray shielding performance and dosimetric optimization at ^{60}Co energies [6,7]. Although the Beer–Lambert law strictly applies to narrow-beam conditions, it provides a robust theoretical framework for defining attenuation targets and comparing shielding efficiency when combined with conservative experimental design and validation.

International recommendations emphasize that irradiation processes must be supported by dosimetric traceability and uncertainty awareness. Standards such as ISO/ASTM 51261 and guidance documents from the International Atomic Energy Agency highlight the importance of calibrated dosimetry systems, reproducible geometry, and transparent reporting of irradiation parameters [8,9,10,11]. While not specifically developed for low-dose small-animal irradiation, these principles are directly applicable to preclinical experimental setups.

Within this framework, the Gamma Irradiation Laboratory (LIG) of the Nuclear Technology Development Center (CDTN) operates a multipurpose ^{60}Co irradiator in which irradiation planning is performed using facility-specific routines that integrate geometric configuration, source activity, and operational constraints. For low-dose applications, maximizing the source-to-sample distance represents a practical strategy to reduce dose rate and improve control over short irradiation times, as recommended in recent preclinical dosimetry studies [12].

In this context, the present work describes the development and validation of a low-dose gamma radiation dosimetry protocol (~ 41.3 mGy) implemented at LIG/CDTN. The protocol integrates attenuation modeling based on the Beer–Lambert law with facility-routine operational planning, emphasizing reproducibility, dosimetric traceability, and compliance with radiological protection standards. By detailing the physical principles, geometric constraints, and operational considerations involved, this study aims to provide a methodological reference for preclinical investigations requiring controlled low-dose gamma irradiation.

2. MATERIALS AND METHODS

2.1. Gamma Irradiation Facility

The dosimetric protocol was developed and implemented at LIG/CDTN. The facility operates a multipurpose gamma irradiator equipped with a sealed ^{60}Co source, emitting photons with nominal energies of 1.17 and 1.33 MeV. The irradiator allows irradiation at different source-to-sample distances, enabling the adjustment of dose rates according to experimental requirements.

All irradiations were conducted following the routine operational procedures established by the LIG/CDTN, ensuring compliance with national radiological protection regulations and institutional safety protocols.

2.2. Dosimetric Planning and Attenuation Criterion

Dosimetric planning was based on the Beer–Lambert exponential attenuation law, which describes the attenuation of gamma radiation intensity as a function of material thickness and linear attenuation coefficient. This formalism was used to define an attenuation criterion and to guide the selection of shielding configuration employed during irradiation, expressed as (Equation 1):

$$I = I_0 e^{-\mu x} \quad (1)$$

Where:

I =transmitted intensity,

I_0 =incident intensity,

μ =linear attenuation coefficient of the material (cm^{-1}) and

x =material thickness (cm).

A target transmitted fraction of the incident beam was defined in advance to ensure controlled dose reduction. Lead was selected as the shielding material due to its high density and high atomic number, which provide effective attenuation at ^{60}Co photon energies. The attenuation criterion was applied to dimension the effective shielding thickness required to achieve the desired reduction in beam intensity.

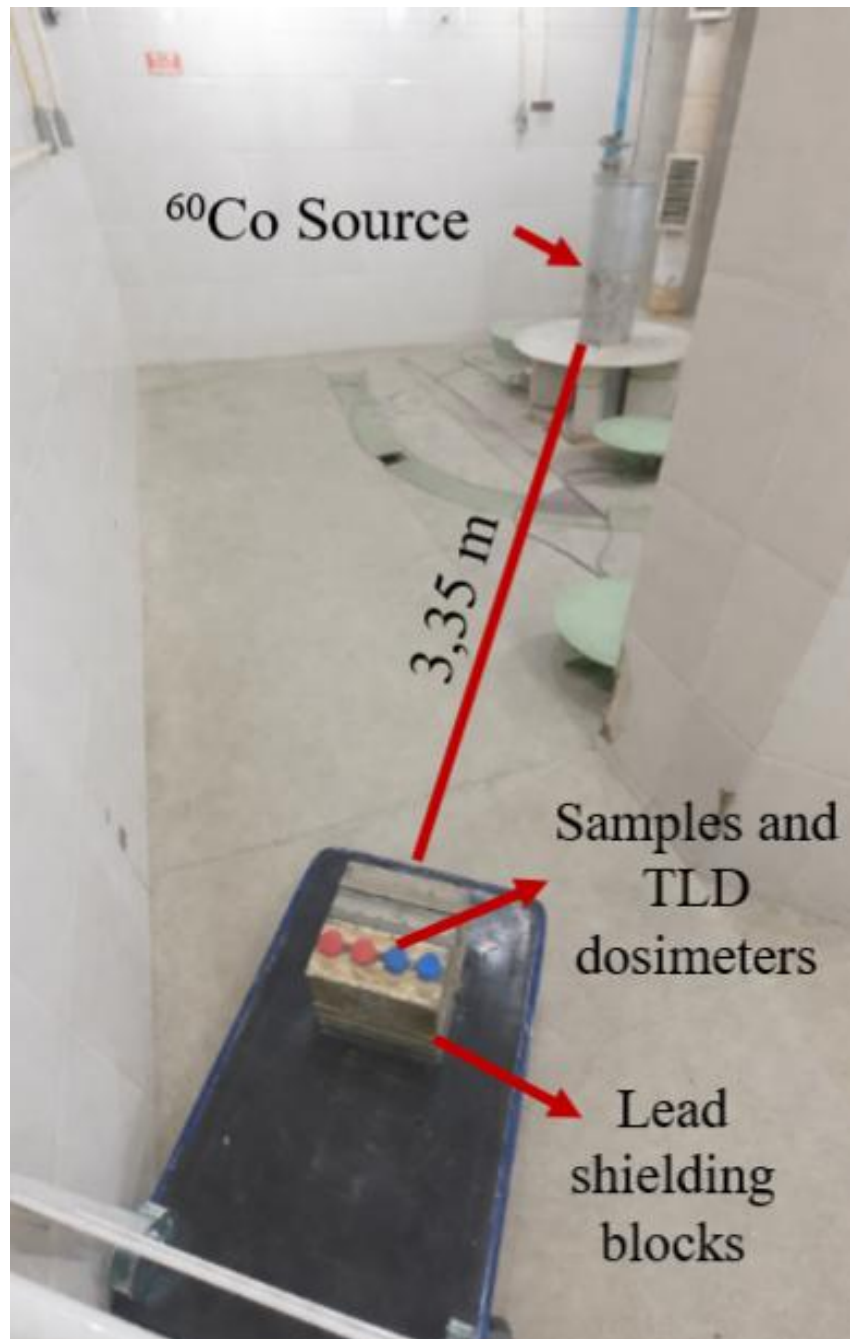
Although the Beer–Lambert law strictly applies to narrow-beam geometries, it was adopted in this study as a conservative theoretical framework for shielding design and dose control, acknowledging that scattering and buildup effects may lead to deviations under realistic irradiation conditions. A comparative analysis of candidate materials was performed to identify the most efficient option for achieving the target transmitted fraction, as presented in Table 1 (Section 3.2).

2.3. Geometric Configuration and Source–Sample Distance

To enable low-dose irradiation in the milliGray range, a conservative geometric configuration was adopted. The samples were positioned at the maximum operational distance available in the irradiator, 3.35 m from the sealed ^{60}Co source (Figure 1). This configuration was selected to minimize dose rate at the irradiation position and to improve temporal control during short exposure times.

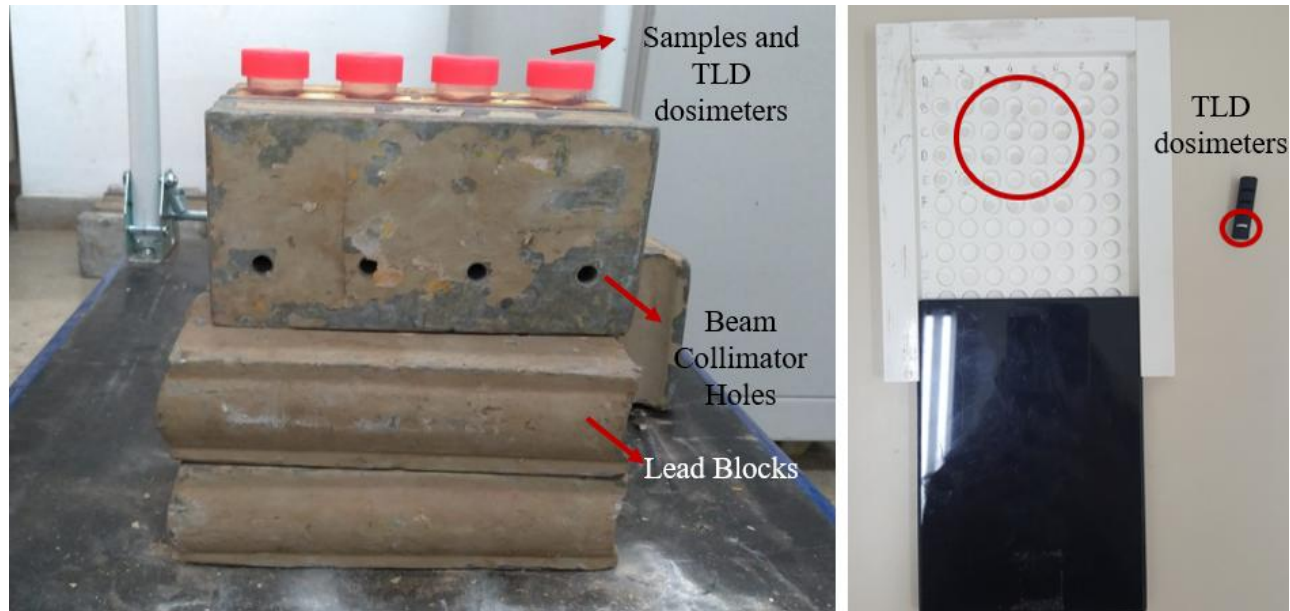
Samples were placed on a mobile support system provided by the facility, allowing reproducible positioning relative to the source. Lead blocks were used to stabilize the experimental setup and to ensure consistent geometry during irradiation (Figure 2).

Figure 1: Experimental irradiation setup showing the source-to-sample geometry (3.35 m) and the arrangement of lead shielding blocks used for attenuation and mechanical stabilization.



Source: the authors

Figure 2: Experimental irradiation setup showing the sample holder containing the TLD dosimeters positioned at a source-to-sample distance of 3.35 m. The assembly includes lead shielding blocks used for attenuation and mechanical stabilization, as well as beam collimator holes that partially define the irradiation geometry. The proximity of shielding elements to the dosimeters contributes to scattered radiation and buildup effects.



Source: the authors

2.4. Exposure Time Determination

The exposure time required to achieve the target absorbed dose of approximately 41.3 mGy was determined using the internal operational calculation routine of the LIG/CDTN. This routine integrates source activity, geometric parameters, and distance from the source to estimate the irradiation time necessary to deliver the prescribed dose.

Under the selected configuration, the irradiation time was on the order of a few seconds (approximately 2 s), with the understanding that this value may increase over time as a function of source decay. All irradiations were performed using the same geometric arrangement and operational parameters to ensure reproducibility.

2.5. Radiological Protection and Reproducibility Considerations

All irradiation procedures were conducted in accordance with national radiological protection standards and institutional safety guidelines. The use of fixed geometry, conservative distance selection, and standardized operational routines ensured dosimetric traceability and minimized uncertainties associated with positioning and exposure time.

This methodological approach was designed to provide controlled, reproducible delivery of low gamma doses, suitable for preclinical experimental applications requiring precise dose control in the milliGray range.

3. RESULTS AND DISCUSSIONS

3.1. Dose Delivery and Reproducibility

These results validate implementation of the proposed dosimetric protocol enabled the controlled delivery of low gamma radiation doses in the milliGray range, with a target absorbed dose of approximately 41.3 mGy. Dosimetric verification using thermoluminescent dosimeters (TLDs) resulted in a measured absorbed dose of (41.3 ± 2.1) mGy ($k=1$), demonstrating good agreement with the planned value.

The use of a fixed and conservative geometric configuration, combined with facility-routine operational planning, ensured consistent dose delivery across irradiations performed under identical conditions. The maximum operational source-to-sample distance (3.35 m) resulted in reduced dose rates, allowing precise temporal control even for short exposure times on the order of a few seconds.

Reproducibility was evaluated through repeated irradiations ($n = 5$), yielding a coefficient of variation below 5%, which indicates satisfactory repeatability for low-dose applications. This reproducibility was achieved through strict control of geometric parameters, including source position, sample placement, and shielding arrangement. The

use of a mobile support system with standardized positioning, together with lead blocks for mechanical stabilization, minimized positional variability between irradiations. This approach is particularly relevant for low-dose experiments, in which small geometric deviations may lead to proportionally large uncertainties in absorbed dose. These results confirm the reliability and robustness of the proposed dosimetric methodology under realistic irradiation conditions.

3.2. Effectiveness of the Attenuation Strategy

The attenuation strategy based on the Beer–Lambert exponential law proved effective for defining a conservative attenuation criterion and guiding the selection of shielding configuration. The adoption of lead as the attenuating material ensured efficient reduction of the gamma beam intensity at ^{60}Co photon energies. Although the Beer–Lambert law strictly applies to narrow-beam conditions, its application in this study provided a practical and theoretically grounded framework for dose control.

In realistic irradiation geometries, scattered radiation and buildup effects may reduce the apparent attenuation predicted by idealized models. However, by combining attenuation modeling with increased source-to-sample distance and fixed geometry, the protocol mitigated the influence of these effects. The resulting irradiation conditions were therefore suitable for low-dose applications, without requiring complex correction factors or additional collimation systems.

Table 1 presents the calculated shielding thicknesses required for different materials based on their linear attenuation coefficients (μ), according to the Beer–Lambert attenuation criterion adopted in this study. The results indicate a strong dependence of the required shielding thickness on material composition. High-density, high atomic number materials required significantly smaller thicknesses to achieve the target attenuation. Among the evaluated materials, lead exhibited the most favorable attenuation performance, requiring the smallest thickness to meet the predefined transmitted fraction. This result directly supported

the selection of lead as the shielding material in the experimental irradiation setup. The difference between theoretical attenuation and experimental conditions highlights the importance of considering scattered radiation contributions, particularly in non-collimated geometries. This reinforces the role of experimental validation using dosimeters, as performed in this study.

Table 1: Calculated shielding thicknesses for different shielding materials based on their linear attenuation coefficients (μ).

Material	μ (cm ⁻¹)	x (cm)
Copper	0.15	13.5
Steel	0.2	10.12
Lead	0.6	3.4
Brass	0.25	8.1
Aluminum	0.025	81.0

Source: the authors

3.3. Geometric Stability and Field Uniformity

The selected irradiation configuration produced a radiation field with adequate spatial uniformity for preclinical applications involving small samples or experimental holders. The relatively large source-to-sample distance contributed to a more homogeneous photon fluence across the irradiation plane, reducing local dose gradients that may arise at shorter distances.

Geometric stability was further reinforced by the use of lead shielding elements not only for attenuation but also for mechanical stabilization of the setup. This dual function enhanced repeatability and minimized setup-related uncertainties, which are critical in low-dose dosimetry where absolute dose values are small.

3.4. Operational Practicality and Traceability

A key outcome of this work is the demonstration that low-dose gamma irradiation can be reliably implemented within the routine operational framework of a multipurpose irradiation facility. The use of the LIG/CDTN internal planning routine, which integrates

source activity, geometry, and distance, ensured dosimetric traceability and alignment with institutional quality and safety procedures.

The irradiation time required to deliver the target dose (~ 2 s under the selected configuration) was compatible with the operational resolution of the facility and can be readily adjusted over time to account for source decay. This adaptability reinforces the long-term applicability of the protocol and its suitability for repeated experimental campaigns.

3.5. Methodological Implications for Preclinical Dosimetry

The results demonstrate that the proposed protocol provides a robust dosimetric framework for low-dose gamma irradiation, emphasizing simplicity, reproducibility, and safety. Rather than relying on complex correction schemes or highly specialized instrumentation, the methodology leverages conservative geometric choices, attenuation modeling, and standardized operational procedures.

By explicitly documenting the physical assumptions, geometric constraints, and operational parameters involved, this study contributes to improved transparency and reproducibility in experimental dosimetry. The approach can be adapted to other multipurpose gamma irradiation facilities, provided that facility-specific characteristics are properly accounted for. As such, the protocol offers a practical reference for future preclinical studies requiring controlled low-dose gamma irradiation.

3.6. Influence of Scattered Radiation

The experimental configuration includes shielding elements positioned in close proximity to the dosimeters (Figure 2), which may contribute to scattered radiation and buildup effects. In broad-beam geometries, scattered photons originating from shielding materials and surrounding structures increase the detected dose compared to ideal narrow-beam conditions. This effect partially explains deviations from Beer–Lambert predictions.

However, the impact of scattered radiation was mitigated by the large source-to-sample distance (3.35 m), which reduces photon fluence and angular spread. Additionally, the reproducibility results indicate that the scattered component remains stable under fixed geometric conditions.

Therefore, although scattering contributes to the absolute dose, it does not compromise the consistency and applicability of the proposed dosimetric protocol.

4. CONCLUSIONS

This work focuses exclusively on the dosimetric methodology implemented at the LIG/CDTN and does not address biological outcomes.

In this work, a dosimetric protocol for low-dose gamma irradiation using a multipurpose ^{60}Co irradiator was developed and validated with emphasis on reproducibility, traceability, and operational simplicity. The methodology was designed to enable controlled delivery of absorbed doses in the mGy range, addressing key challenges associated with low-dose experiments, such as sensitivity to geometric variations and short irradiation times.

The protocol integrates attenuation modeling based on the Beer–Lambert exponential law with a conservative geometric configuration and facility-routine operational planning. The adoption of the maximum operational source-to-sample distance effectively reduced dose rates and improved temporal control, while the use of lead shielding provided consistent attenuation and mechanical stabilization of the irradiation setup. These elements collectively minimized setup-related uncertainties and ensured reproducible dose delivery under routine operational conditions.

The proposed protocol is particularly suitable for small samples and experimental holders with characteristic dimensions on the order of a few centimeters (typically up to 5 cm), for which field uniformity is maintained under the selected irradiation geometry. Larger

samples may experience increased dose gradients due to geometric divergence and scattering effects, representing a limitation of the current configuration.

Future improvements may include the implementation of dedicated collimation systems and detailed Monte Carlo simulations to further quantify scattering contributions and optimize dose uniformity. The agreement between planned and experimentally measured doses further supports the robustness of the proposed protocol.

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CONTRIBUTORSHIP

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Writing – review and editing: SWG, MAZ

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Supervision: MAS, OACP

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study and the derived data supporting the conclusions of this study are available upon reasonable request to the corresponding author.

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