

MCMEG

MONTE CARLO MODELLING EXPERT GROUP

Intercomparison Exercise Vol.3

The MCMEG 2026 Intercomparison Exercise

The *Monte Carlo Modelling Expert Group (MCMEG)* 2026 is an international collaborative network dedicated to advancing Monte Carlo (MC) radiation transport modelling and simulation with applications in radiation protection and dosimetry. Today, the MCMEG includes 118 members from research institutes across several countries, promoting shared learning, benchmarking initiatives, and the development of reliable computational methodologies for complex radiological scenarios. New participants are continually welcomed, maintaining the group as an open, cooperative scientific platform.

In 2016, MCMEG conducted its first intercomparison exercise involving the modelling and simulation of a 6 MV LINAC photon beam using different MC codes. The resulting dose distributions were validated against experimental measurements of PDD and TPR curves obtained at the National Cancer Institute (INCA) in Rio de Janeiro, Brazil (T. Fonseca, Mendes, et al. 2017). This initiative demonstrated the impact of modelling assumptions, geometric representations, and code-specific implementations on simulation accuracy, reinforcing the value of shared benchmarking and harmonized methodology.

In 2017, the second intercomparison exercise focused on the simulation of a prostate radiotherapy treatment protocol, aiming to evaluate dose distributions in both the target volume and surrounding organs (T. Fonseca, Antunes, et al. 2020). Four Brazilian research groups—IPEN (São Paulo), the Faculty of Medicine and the Department of Nuclear Engineering of UFMG, Hospital Luxemburgo (Belo Horizonte), and CDTN (Belo Horizonte)—participated using various Monte Carlo codes, including MCNP6, MCNPX, EGS++, and BEAMnrc/DOSXYZnrc/EGSnrc (Werner et al., 2017; Goorley et al., 2012; Mainegra-Hing et al., 2017). The simulated dose distributions were compared to experimental results obtained using LiF:Mg,Ti thermoluminescent dosimeters positioned within an Alderson-Rando pelvic phantom, providing a detailed evaluation of inter-code consistency and dosimetric agreement.

NOW, the 2026 intercomparison exercise extends this collaborative effort to the Monte Carlo modelling of a clinical diagnostic X-ray system (VMI Pulsar 800 Plus) operated at the Calibration and Dosimetry Laboratory of the Nuclear Technology Development Center (CDTN/CNEN-Brazil). The exercise was designed to evaluate the consistency of independent simulations under well-defined experimental irradiation conditions, including beam-quality characterization and phantom-based dosimetric analysis.

The exercise involves the simulation of diagnostic-energy X-ray beams generated at tube voltages from 60 to 100 kVp and the comparison of computational results with experimental measurements obtained at the laboratory. The evaluated quantities include parameters related to X-ray beam attenuation, air kerma, homogeneity, backscatter contribution, and the radiological response of water and resin materials.

New participants are warmly invited to join this exercise. Previous intercomparison publications provide methodological background and reference workflows (T. Fonseca, Mendes, et al. 2017; T. Fonseca, Antunes, et al. 2020). The compiled results will contribute to a manuscript for submission to an international peer-reviewed journal.

Objective

The objective of this exercise is to evaluate the agreement between independent Monte Carlo simulations and experimental measurements in the radiological characterization of a clinical diagnostic X-ray system. Participants are invited to perform the simulations for the two proposed cases and report their calculated results to the MCMEG team.

Case 1 – X-ray beam characterization: Participants will characterize the X-ray beam using aluminum attenuation data, reporting air kerma, attenuation coefficient, first and second half-value layers (HVLs), and the homogeneity coefficient.

Case 2 – Phantom-based dosimetry: Participants will evaluate dosimetric quantities using cylindrical water and resin phantoms, with emphasis on backscatter response, depth-dose behavior, and resin-to-water conversion relationships.

The MCMEG team will compile and compare the results from all participants with the experimental data and across different Monte Carlo approaches, including codes, spectral inputs, geometry modelling, and scoring strategies. Before publication, all participants will be informed of any significant discrepancies identified in their results and will have the opportunity to review and clarify their calculations.

1 Computational setup

X - Ray Spectrum

The X-ray emission spectrum is not directly provided by the clinical system. Therefore, participants may use any appropriate spectrum-generation method or software. Online tools and databases such as *SpekPy* (Vorbau and Poludniowski 2024), *CTDose* (Department of Medical Physics, University of Crete n.d.), *SPEKTR* (Punnoose et al. 2016), and *SpekCalc* (Poludniowski et al. 2009) are suggested as possible options, but their use is not mandatory. Participants are free to select or generate the X-ray spectra using the tools or approaches of their choice, provided that the experimental conditions defined in this exercise are preserved.

The spectra must correspond to a tungsten-target clinical X-ray tube operated at 60, 70, 80, 90 and 100 kVp, with a constant tube current-time product of 20 mAs. An inherent filtration of $FI = 1.6 \pm 0.1$ mmAl, experimentally determined according to the ISO 4037-1 methodology (ABNT 2020), must be applied to all tube voltages.

The spectrum-generation parameters listed in Table 1 must be reported by each participant to allow comparison and interpretation of the simulated results.

Table 1: Parameters to be reported for X-ray spectrum generation.

Parameter	**Value / Information**
Software	Name and version
Tube voltage	60, 70, 80, 90, and 100 kVp
Target material	Tungsten
Tube current-time product	20 mAs
Inherent filtration	1.6 ± 0.1 mmAl
Anode angle	(if used) To be reported
Energy-bin width	(if used) To be reported
Spectrum normalization method	(if used) To be reported

1.1 Case 1 – X-ray beam characterization

The scoring region is defined as a circular plane with a radius of 1 cm, positioned at the origin of the coordinate system, 100 cm from the X-ray source. The three-dimensional geometry reproduces the narrow-beam condition, as illustrated in Figure 1. This geometry follows the attenuation exercise and is designed to minimize the contribution of scattered radiation to the scoring region.

The computational model is similar to Exercise 4 of Chapter 6 (Photon Attenuation Law) in the book *Computational Experiments of Radiation Physics* (Paixão and T. C. F. Fonseca 2023).

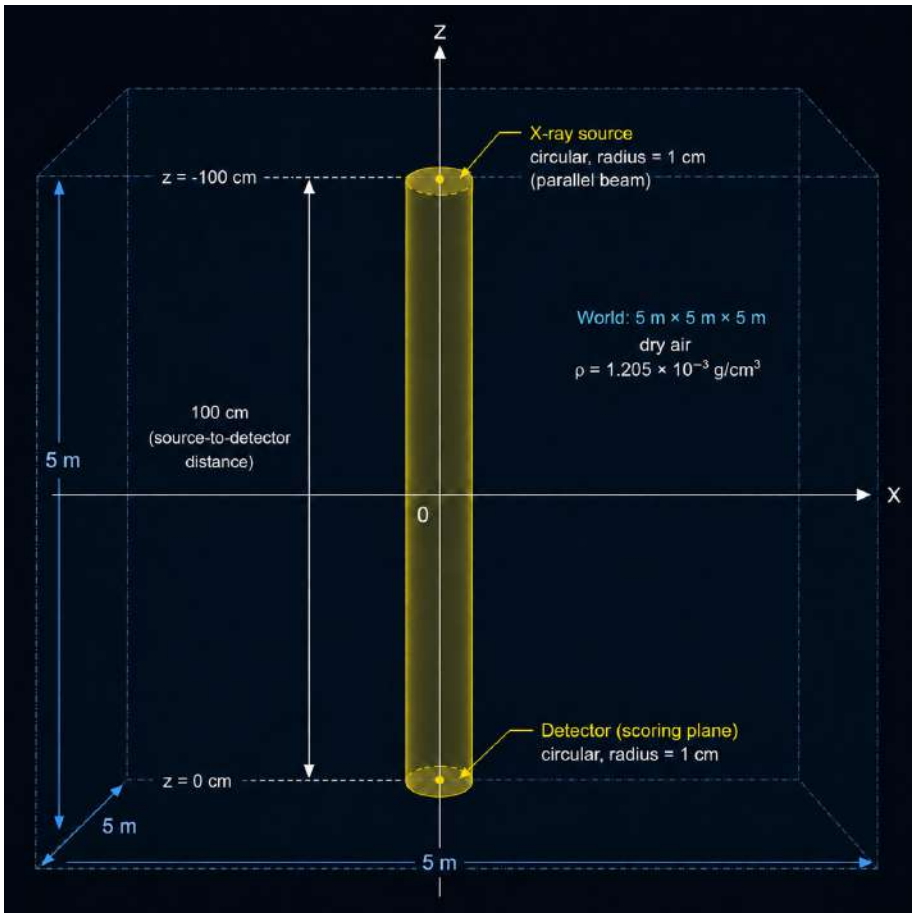


Figure 1: Schematic representation of the computational geometry (not in scale).

Table 2 summarizes the parameters used in the modelling and simulations. Participants may adapt code-specific implementation parameters, such as source sampling, particle transport settings, scoring resolution, and number of histories, provided that the experimental setup geometry, irradiation conditions, material definitions, and required output quantities specified for this exercise are preserved. Table 3 shows the the total aluminum thicknesses to be simulated.

Table 2: Simulation parameters used in the modelling and simulations.

8Parameter	**Value / Description**
World material	Dry air
World dimensions	$5 \times 5 \times 5$ m^3
Air density	1.205×10^{-3} g/cm^3
Source type	Circular photon source
Source radius	1 cm
Beam geometry	Parallel narrow beam
Scoring region	Circular plane
Scoring-region radius	1 cm
Source-to-scoring distance	100 cm
Attenuating material	Aluminum
Aluminum density	2.699 g/cm^3
Aluminum longitudinal position	30 cm from the X-ray source
Aluminum lateral position	Centered on the beam axis ($x = 0$, $y = 0$)

Table 3: Total aluminum thicknesses used for the attenuation curves.

Tube Voltage (kVp)	**Total Aluminum Thicknesses (mmAl)**
60	0; 1.00; 1.50; 1.60; 1.70; 1.85; 2.00; 3.50; 4.50; 6.00
70	0; 1.00; 1.85; 2.00; 3.50; 4.00; 4.50; 5.00; 6.00
80	0; 1.00; 1.50; 2.00; 2.25; 3.00; 4.00; 5.00; 5.50; 6.00; 7.00; 9.00
90	0; 1.00; 2.00; 2.20; 2.35; 2.60; 3.50; 4.50; 5.50; 6.10; 6.50; 8.00; 9.00
100	0; 2.00; 2.75; 2.85; 2.95; 3.00; 4.00; 5.00; 6.00; 7.00; 8.00; 8.50; 10.00

To be calculate:

For each tube voltage, provide the

- attenuation curve
- effective attenuation coefficient, μ_{eff}
- first half-value layer, HVL_1
- second half-value layer, HVL_2
- homogeneity coefficient, HC

1.2 Case 2 – Phantom-based dosimetry

Case 2 will be performed using two distinct phantoms: one made of water and the other of resin. The additional parameters required for Case 2 are summarized in Table 4. The X-ray spectra and transport settings adopted in Case 1 must be maintained. The source geometry must then be modified to reproduce a divergent cone beam with a field size of 12×13 cm^2 at the 100 cm reference plane. A cylindrical phantom should be positioned at this reference plane. Figure 2 shows a schematic representation of the Case 2 geometry to be modelled.

For the backscatter factor (BSF) calculation, two simulations must be performed using the same source, spectrum, field size and scoring conditions, one without the phantom to obtain K_i, and one with the phantom to obtain K_e (International Atomic Energy Agency 2007; Paixão, Oliveira, and Vieira 2021).

The BSF must be calculated as:

$$BSF = \frac{K_e}{K_i}$$

Simulations must be performed for the water phantom and for the resin phantom using the same scoring positions.

Table 4: Additional simulation parameters for the cylindrical phantom assessment.

Parameter	**Value / Description**
Phantom geometry	Cylinder with diameter and height of 10 cm
Beam geometry	Divergent beam
Reference plane	Table plane
Source-to-reference plane distance	100 cm
Field size at reference plane	12×13 cm^2
Phantom base position	At the reference plane
Water density	1.000 g/cm^3
Resin material	Solid 3D-printing resin
Resin material	Clear Resin V4 (Formlabs Inc.)
Resin density	1.09 g/cm^3
Resin elemental composition	Approximated by methyl methacrylate ($C_5H_8O_2$)
Resin composition reference	Wegner et al. (2023) (Wegner et al. 2023)
Air-kerma scoring region	Circular plane of 1 cm radius
Air-kerma scoring position	Phantom entrance surface
Dose-Scoring TLD detector	MTS-N (LiF:Mg,Ti)
TLD geometry	Cylindrical disc, 4.5 mm diameter and 0.9 mm thickness
TLD material in the simulation	Lithium fluoride (LiF)
Dose-scoring position	Center at 0.30, 1.00, 5.00 cm from the entrance surface
Scored quantities	Air kerma and absorbed dose per primary particle (Gy/history)

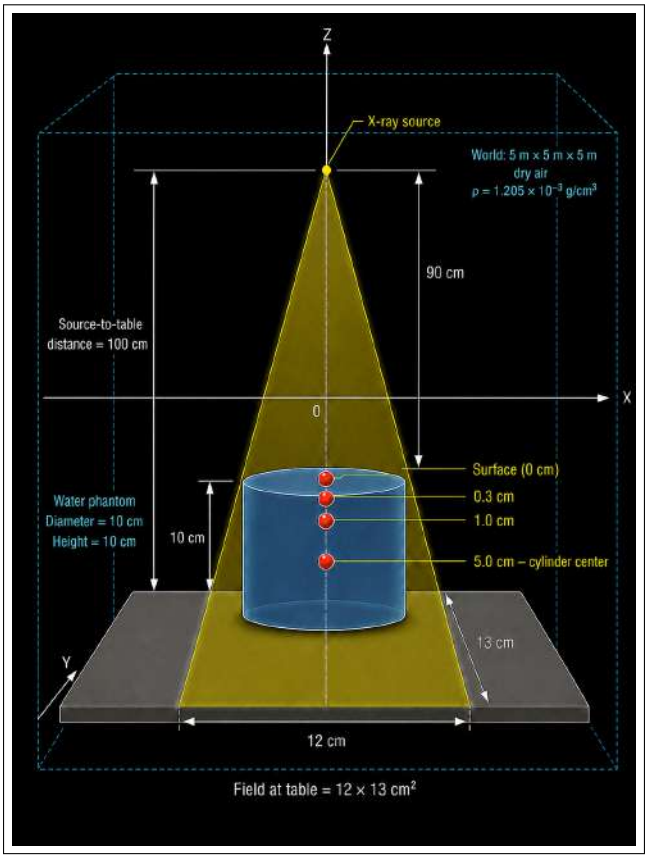


Figure 2: Schematic representation of the computational geometry used in Case 2.

To be calculate for the water and resin:

For each tube voltage, provide the

- backscatter factor (BSF)
- relative dose response at 0.30, 1.00, and 5.00 cm
- relative depth-dose response
- dose ratio and (BSF) between water and resin at each scoring position

2 Information Data

The parameters explicitly defined in this document must not be modified by participants. Code-specific parameters that are not explicitly prescribed may be selected by each participant but must be fully reported. Monte Carlo air-kerma and absorbed-dose results must be reported per primary particle, in Gy/particle or mGy/particle. Absolute X-ray tube output is not required. The experimental HVL values obtained from the ionization chamber attenuation data are provided in Table 5 and must be used as reference values for comparison with the simulation results.

Table 5: Experimental first Half-Value Layer (1st HVL) values measured with an ionization chamber for different tube voltages.

Tube Voltage (kVp)	**Tube Current-Time Product (mAs)**	**1st HVL (mmAl) Ionization chamber**
60	20	1.68 ± 0.06
70	20	1.93 ± 0.06
80	20	2.19 ± 0.07
90	20	2.44 ± 0.08
100	20	2.97 ± 0.09

It is recommended that participants complete the exercises on photon attenuation and scattered radiation presented in the book *Computational Experiments of Radiation Physics* (Paixão and T. C. F. Fonseca 2023) before starting this intercomparison exercise.

To be listed as a co-author in the manuscript submission, you will be asked to submit a report on your simulation work. This report, which must be written in English, must contain all essential information:

- Name and Affiliation
- Monte Carlo code and version used
- Complete simulation geometry details
- Complete material details (composition, weight fraction, density)
- Source details (source type, energy spectrum, scoring field*, position, etc.)
- Specify the conditions under which the spectrum was obtained
- Monte Carlo parameters used (user-code*, scoring type — energy, dose, kerma, fluence, etc. — photon and electron cut-off energies, cross-section libraries, number of simulated histories, simulation time, relative error, variance reduction technique, etc.)

- Hardware specifications (number of processors and frequency, RAM, operating system, etc.)
- Simulation results
- Software used for the analyses of your results
- All references used

Send your results by November 14th 2026.

Note: The results (the two excel files filled with your results) have to be sent to mcmeg.ufmg@gmail.com

Note: Data processing and curve fitting should be performed using scientific software appropriate to the selected fitting method.

To standardize the insertion of materials in the simulations, the Compendium of Material Composition Data for Radiation Transport Modeling should be used as the reference source for material definitions (Detwiler et al. 2021).

Bibliography

ABNT (May 7, 2020). *ABNT NBR ISO 4037-1:2020: Proteção radiológica – Radiação X e gama de referência para calibração de dosímetros e medidores de taxa de dose, e para determinação de suas respostas em função da energia dos fótons – Parte 1: Características das radiações e métodos de produção*. Adoção idêntica da ISO 4037-1:2019. Rio de Janeiro, Brazil: Associação Brasileira de Normas Técnicas.

Department of Medical Physics, University of Crete (n.d.). *X-ray Spectrum Generator for Monte Carlo Calculations (ctdose)*. Web Tool. URL: http://ctdose-iqurad.med.uoc.gr/xsg/.

Detwiler, R.S. et al. (2021). *Compendium of Material Composition Data for Radiation Transport Modeling*. Tech. rep. Richland, WA: Pacific Northwest National Laboratory. URL: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-15870Rev2.pdf.

Fonseca, T.C.F., P.C.G. Antunes, et al. (2020). "MCMEG: Intercomparison exercise on prostate radiotherapy dose assessment". In: *Radiation Physics and Chemistry* 167. Special issue dedicated to the 14th International Symposium on Radiation Physics, p. 108295. ISSN: 0969-806X. DOI: https://doi.org/10.1016/j.radphyschem.2019.04.045. URL: https://www.sciencedirect.com/science/article/pii/S0969806X18311186.

Fonseca, T.C.F., B.M. Mendes, et al. (2017). "MCMEG: Simulations of both PDD and TPR for 6MV LINAC photon beam using different MC codes". In: *Radiation Physics and Chemistry* 140. 2nd International Conference on Dosimetry and its Applications (ICDA-2) University of Surrey, Guildford, United Kingdom, 3-8 July 2016, pp. 386–391. ISSN: 0969-806X. DOI: https://doi.org/10.1016/j.radphyschem.2017.03.048. URL: https://www.sciencedirect.com/science/article/pii/S0969806X1730381X.

International Atomic Energy Agency (2007). *Dosimetry in Diagnostic Radiology: An International Code of Practice*. Tech. rep. 457. Vienna: International Atomic Energy Agency. URL: https://www-pub.iaea.org/MTCD/Publications/PDF/TRS457_web.pdf.

Monte Carlo Modelling Expert Group (MCMEG) (2026). Google Groups. URL: https://groups.google.com/forum/#!forum/mcmeg (visited on 03/05/2026).

Paixão, Lucas and Telma Cristina Ferreira Fonseca (2023). *Computational Experiments of Radiation Physics*. 1st ed. Vol. 1. Independently published. 67 pp. ISBN: 9798396739123. URL: https://www.amazon.com.br/Experimentos-Computacionais-F%C3%ADsica-Radia%C3%A7%C3%B5es-Portuguese/dp/B09SL4B8KJ/.

Paixão, Lucas, Bruno B. Oliveira, and Leandro A. Vieira (2021). "Backscatter Factors Calculation for Intraoral Dental Radiology". In: *Biomedical Physics & Engineering Express* 7.4, p. 045009. DOI: 10.1088/2057-1976/ac02a7.

Poludniowski, Gavin et al. (2009). "SpekCalc: A Program to Calculate Photon Spectra from Tungsten Anode X-ray Tubes". In: *Physics in Medicine and Biology* 54.19, N433–N438. DOI: 10.1088/0031-9155/54/19/N01.

Punnoose, J. et al. (2016). "Technical Note: spektr 3.0—A computational tool for X-ray spectrum modeling and analysis". In: *Medical Physics* 43.8, pp. 4711–4717. DOI: 10.1118/1.4955438.

Vorbau, Robert and Gavin Poludniowski (2024). "Technical Note: SpekPy Web—Online X-ray Spectrum Calculations Using an Interface to the SpekPy Toolkit". In: *Journal of Applied Clinical Medical Physics* 25.3, e14301. DOI: 10.1002/acm2.14301. URL: https://spekpy.smile.ki.se/.

Wegner, Marie et al. (2023). "Development and characterization of modular mouse phantoms for end-to-end testing and training in radiobiology experiments". In: *Physics in Medicine & Biology* 68, p. 085009. DOI: 10.1088/1361-6560/acc566.