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Dosimetric Validation of Computed Tomography Protocol Optimization Using TOPAS

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1. Introduction

Computed tomography (CT) is a non-invasive imaging technique that uses ionizing radiation to generate detailed cross-sectional images of the internal structures of the body, as described by the World Health Organization (2021). In certain situations, conventional methods, such as the measurement of the computed tomography dose index (CTDI), have been questioned regarding their applicability. In this context, an alternative approach for dose estimation in CT examinations is the use of simulations based on the Monte Carlo (MC) method [1]. The aim of this study is to present a Monte Carlo simulation of the optimization process of computed tomography protocols for head and chest examinations in adult patients at the Hospital das Clínicas of Pernambuco (HC-UFPE), as well as to compare the simulated results with experimental data.

2. Methodology

The computational modeling was developed using the TOPAS (Tool for Particle Simulation) framework, based on Geant4. The simulated geometry consisted of a cylindrical PMMA phantom filled with water, with a radius of 150 mm, containing five ionization chambers (center, top, bottom, right, and left) positioned at 140 mm from the center for peripheral measurements.

During the development of the simulation setup, two critical refinements were implemented to ensure the accuracy of the model in relation to the experimental conditions: (1) Beam modeling and collimation: a primary source with a flat distribution and a geometric aperture of 45° was defined, simulating the CT scanner fan beam; (2) Bow-tie filter geometry: the parametric curvature of the (.stl) file was smoothed, enabling proper peripheral attenuation that reflects the homogeneous dose distribution characteristic of the chest protocol. The simulations were performed using 900 million particle histories. The absorbed dose obtained in Gy per history was multiplied by X-ray tube photon yield factor (calibration factor) to estimate the total simulated dose.

The object was modeled as a cylinder with a radius of 150 mm, corresponding to the same 300 mm diameter as the real body phantom. It was entirely filled with G4_WATER (liquid water), a material adopted by Geant4 as the gold standard for absorbed dose calculations. To emulate the measurement of the CTDI, the interior of the phantom was equipped with five smaller cylinders acting as ionization chambers. Each “chamber” had a diameter of 1 cm (5 mm radius) and a total length of 10 cm.

To simulate the real examination, the computational phantom was coupled to the translation table. Its longitudinal coordinate was programmed to move in real time according to the linear speed of the table, allowing the X-ray fan beam to sweep across the volume during gantry rotation.



Figure 1: Philips Phantom Incisive CT scanner at HC-UFPE.

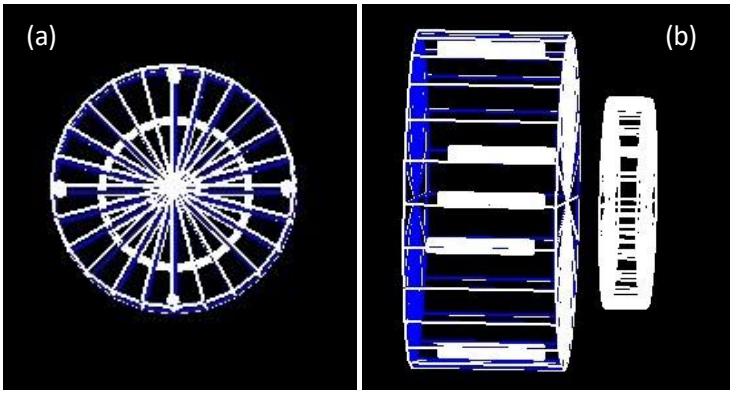

Figure 2: Phantom developed for Monte Carlo (MC) simulation.
(a) Top view (axial plane) of the phantom and (b) lateral view (sagittal plane) of the phantom.

For the simulation, the protocol corresponding to the chest examination adopted at the Hospital das Clínicas of the Federal University of Pernambuco was used, as described in Table I and based on the parameters established in Amorim (2025) [2], employing a clinical phantom with the same characteristics as the one used in the simulation (Figure 2).

Table I: Standard chest CT protocol at HC-UFPE.

Exam: Chest					
Protocol	**Rotation time (min)**	**Voltage (kVp)**	**Pitch**	**Tube current-time product (mAs)**	**CTDIvol (mGy)**
Standard	0.75	120	0.80	103	8.67
Proposal 1	0.75	120	0.80	100	7.29
Proposal 2	0.75	120	0.65	103	4.74
Proposal 3	0.75	120	0.65	100	5.72
Proposal 4	0.75	120	0.80	94	10.09
Proposal 5	0.75	120	0.65	94	3.34

3. Results and Discussion

3.1. Data Analysis:

According to Amorim (2025) [2], in the analysis of chest CT protocols, Proposal 5 showed the best performance compared to the other evaluated alternatives. In relation to the standard protocol, this proposal resulted in a 61.5% reduction in CTDIvol. Proposals 2 and 3 achieved reductions of 45.3% and 34.0%, respectively. However, despite the observed dose reductions, the overall analysis indicates that the implemented modifications did not surpass the performance of the standard protocol, which remained the most appropriate option for chest examinations, as stated by the author.

The results demonstrate that the reduction in pitch, combined with a decrease in the tube current–time product, directly influenced the energy deposition in the phantom, resulting in the observed reduction in CTDIvol in the simulations. Among the evaluated protocols, Proposal 5 presented the lowest dose value, indicating that the combination of lower mAs and pitch adjustment was the most effective in reducing patient exposure.

3.2. Monte Carlo Simulation – TOPAS Code:

For the evaluation of CTDIvol (Figure 3), the simulation was performed based on the suggestion that showed the best performance, corresponding to Protocol 5. The comparison between the simulated results and the reference values of this protocol demonstrated good agreement, with values of 3.61 mGy for the simulation and 3.34 mGy for Protocol 5. Thus, an absolute difference of 0.27 mGy was observed, equivalent to approximately 8.1%, indicating that the computational model was able to adequately reproduce the dose levels of the analyzed protocol.

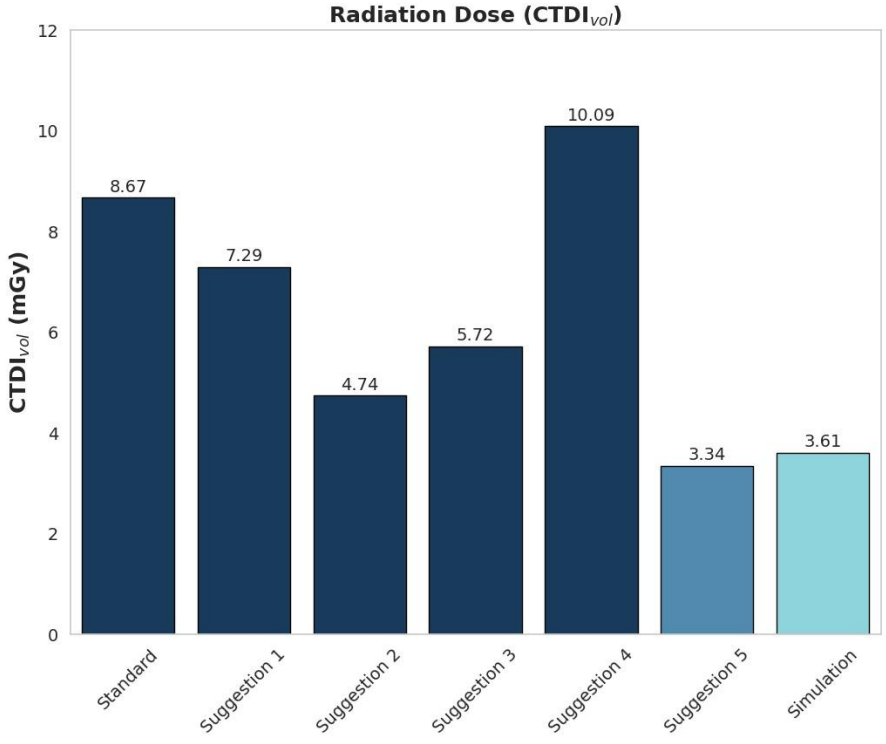

Figure 3: Simulated CTDIvol data

The approximately 8% difference between the simulated and experimental values (Figure 3) can be considered acceptable for dosimetric studies based on the Monte Carlo method, especially considering the geometric simplifications adopted in the phantom and the limitations related to fully modeling the tomographic system. Part of this discrepancy may be associated with the idealized representation of the X-ray spectrum, the lack of detailed modeling of the image reconstruction system, and differences between the real and simulated acquisition conditions.

The results reinforce the capability of TOPAS to reproduce physical scenarios and geometrical configurations related to variations in operational parameters and the equipment setup analyzed. The good agreement observed between the simulated and experimental values demonstrates the robustness of the computational modeling approach employed, highlighting the potential of the tool for independent dosimetric validation applications in CT.

The TOPAS platform, based on the Monte Carlo method, is widely recognized for its high accuracy in simulating radiation–matter interactions and is considered the gold standard for dosimetric evaluation. The results obtained in this study demonstrate that the implemented model was able to adequately reproduce the dose levels of the analyzed CT system, despite the simplifications inherent to the modeling process. Therefore, the proposed methodology represents a promising tool for protocol optimization studies and dosimetric assessments, contributing to the application of the ALARA (As Low As Reasonably Achievable) principle in clinical practice.

4. Conclusions

Monte Carlo simulation using TOPAS proved to be a robust and effective approach for independent dosimetric validation in computed tomography, highlighting the importance of detailed modeling of system components, such as the fan beam aperture (45°) and the bow-tie filter, which directly influence dose distribution. The simulated results showed good agreement with the experimental data, with a relative difference of approximately 8%, considered acceptable for dosimetric studies, reinforcing the reliability of the implemented model.

The results demonstrate that TOPAS is capable of accurately reproducing the dose levels of the analyzed CT system, supporting its application as a tool for protocol optimization and dosimetric assessment. In addition, once lower-dose protocols have been identified through Monte Carlo simulations, experimental investigations can be performed to validate these optimized protocols by measuring CTDIvol and other relevant CT performance parameters. This approach may contribute to the implementation of optimized clinical protocols while supporting the ALARA (As Low As Reasonably Achievable) principle in medical imaging.

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