Volume 2, Issue 4

Innovation Series Quarterly

https://journal.academicapress.org/aps/index.php/isq

Research Article

Radiation Dose in Paediatric Patients using Geant4

Lee Yan Lin[1], and Siti Amira Othman[2,*]

[1] Faculty of Applied Sciences and Technology, Universiti Tun Husssein Onn Malaysia, Pagoh, Johor

[2] Faculty of Applied Sciences and Technology, Universiti Tun Husssein Onn Malaysia, Pagoh, Johor; sitiamira@uthm.edu.my

* Correspondence: sitiamira@uthm.edu.my

Keywords:
Geant4
Paediatric Patients
Monte Carlo Simulation
Paediatric Dosimetry
Radiation Protection

Copyright: © 2026 by the authors. Submitted for open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Abstract: *Paediatric patients are more sensitive to ionizing radiation than adults due to their developing organs and longer expected lifetime. Therefore, accurate assessment of radiation dose during computed tomography (CT) examinations is essential for optimizing diagnostic imaging protocols. This study investigates the application of the Geant4 Monte Carlo simulation toolkit to estimate radiation dose distribution in paediatric patients. A computational anthropomorphic phantom representing a five-year-old child was developed to simulate photon interactions within different organs and tissues. X-ray energy spectra corresponding to tube voltages of 80, 100 and 120 kVp were considered to investigate their influence on absorbed dose. Organ-specific energy deposition was evaluated for radiosensitive organs, including the brain, thyroid, lungs, liver and gonads. The proposed simulation framework provides an opportunity to identify dose variations across organs and evaluate optimized imaging parameters. This approach supports improved paediatric radiation protection and dose optimization.*

1. INTRODUCTION

Computed tomography (CT) is an important diagnostic imaging technique that provides detailed anatomical information for the detection and diagnosis of various medical conditions. In paediatric medicine, CT examinations are frequently used to investigate head injuries, respiratory diseases, abdominal abnormalities and other clinical conditions. Despite its diagnostic benefits, CT imaging involves exposure to ionizing radiation. Radiation exposure in children requires particular attention because developing tissues may be more radiosensitive, and children generally have a longer remaining lifespan during which radiation-associated effects may manifest. The radiation dose received by paediatric patients depends on several factors, including:

- X-ray tube voltage (kVp).
- Tube current and exposure time (mAs).
- Scan length.
- Patient age, weight and body dimensions.
- Anatomical position of the organs.
- X-ray energy spectrum and filtration.

Conventional CT dose indicators, such as the volume CT dose index (CTDIvol) and dose-length product (DLP), provide useful information about scanner output. However, these indicators do not directly represent the absorbed dose received by individual organs. Monte Carlo simulation offers an alternative method for estimating organ-specific radiation doses. The Geant4 toolkit provides comprehensive capabilities for simulating photon transport, particle interactions and energy deposition within complex anatomical geometries.

Carver et al. (2015) demonstrated the application of Geant4 for paediatric CT dosimetry and reported an overall average difference of approximately 6% between simulated and measured CTDI values during their validation study. More recently, paediatric computational phantoms have been incorporated into Monte Carlo simulations to improve organ-dose estimation and radiation protection assessments. Therefore, this study proposes a Geant4-based computational framework to investigate radiation dose distribution in paediatric patients undergoing CT examinations.

1.1 Research Objectives

1. To develop a computational paediatric phantom representing a five-year-old child using Geant4.
2. To simulate photon interactions at 80, 100 and 120 kVp.
3. To estimate absorbed radiation doses in selected organs.
4. To investigate the relationship between X-ray tube voltage and organ-specific absorbed dose.
5. To identify suitable imaging parameters that support radiation dose optimization while maintaining diagnostic image quality.

2. LITERATURE REVIEW

2.1 Radiation Exposure in Paediatric Patients

Radiation protection in paediatric imaging is an important aspect of medical physics. Children differ from adults in anatomical dimensions, organ development and radiation sensitivity. The smaller body dimensions of children can result in different radiation absorption and scattering characteristics compared with adults. Consequently, adult CT protocols should not be directly applied to paediatric patients without appropriate adjustment.

The International Commission on Radiological Protection (ICRP) recommends the use of age-specific computational reference phantoms for radiation dose calculations. ICRP Publication 143 (2020) introduced paediatric reference computational phantoms representing newborns and children aged 1, 5, 10 and 15 years. These models provide anatomical representations suitable for estimating organ and tissue doses. More recently, ICRP Publication 156 introduced paediatric mesh-type reference computational phantoms, providing further developments in anatomical modelling and computational dosimetry.

2.2 Monte Carlo Simulation in Medical Dosimetry

Monte Carlo simulation is a computational technique based on random sampling to describe the probability of particle interactions within different materials. In medical imaging, Monte Carlo techniques are used to investigate:

- Photon attenuation.
- Photoelectric absorption.
- Compton scattering.
- Rayleigh scattering.
- Secondary electron production.
- Energy deposition within organs and tissues.

Geant4 is a widely used simulation toolkit developed for modelling particle interactions and radiation transport. Agostinelli et al. (2003) introduced Geant4 as a comprehensive platform for particle simulation, while Allison et al. (2006, 2016) described its subsequent developments and applications. The ability to construct complex geometries and define individual material properties makes Geant4 suitable for paediatric computational dosimetry.

2.3 Organ-Specific Radiation Dose Estimation

Organ-specific dose estimation is important because different organs receive different radiation exposures depending on their anatomical location and proximity to the scanning region. Example as in Table 1.

Table 1. Organ and radiation protection consideration

Organ	Radiation protection consideration
Brain	Direct exposure during head CT
Thyroid	Potential exposure during head and chest imaging
Lungs	Direct exposure during chest CT
Liver	Direct exposure during abdominal CT
Stomach	Direct exposure during abdominal CT
Gonads	Potential direct or scattered exposure depending on scan region

Lee et al. (2012) investigated organ doses in paediatric and adolescent patients using Monte Carlo simulation, considering different patient ages, genders and CT tube voltages. Their findings highlighted the importance of age-specific computational models in estimating organ doses.

2.4 Application of Geant4 in Paediatric CT Dosimetry

Carver et al. (2015) developed and validated a Geant4 radiation transport code for CT dosimetry. Their work demonstrated that simulated CT dose measurements could be compared with experimental measurements using ionization chambers and optically stimulated luminescence dosimeters. A more recent investigation by Attalla et al. (2026) combined GEANT4/GATE simulation with thermoluminescent dosimeter measurements to evaluate absorbed doses in paediatric phantom organs. The study demonstrated good agreement between simulated and experimentally measured doses for several organs. These studies demonstrate the potential of Monte Carlo simulation for improving organ-specific dose assessment in paediatric imaging.

2.5 Research Gap and Innovation

Although Monte Carlo simulation has been widely applied in medical dosimetry, further investigations are valuable in evaluating the influence of X-ray tube voltage on organ-specific dose

distributions in age-specific paediatric models. The proposed study focuses on integrating a five-year-old computational phantom, realistic X-ray energy spectra and Geant4 radiation transport simulation.

The main innovation is the development of a computational framework that enables systematic comparison of organ doses under different CT operating conditions. This approach may provide useful information for developing optimized paediatric imaging protocols and reducing unnecessary radiation exposure.

3. METHODOLOGY

The proposed methodology consists of six stages: computational phantom development, X-ray source modelling, Geant4 geometry construction, Monte Carlo simulation, organ dose calculation and dose optimization. A computational anthropomorphic phantom representing a five-year-old child will be developed for radiation dose assessment. The phantom should represent the anatomical characteristics and tissue composition of a paediatric patient. The model may be developed using:

- ICRP paediatric reference computational phantom.
- MIRD-based mathematical phantom.
- Voxel-based anthropomorphic phantom.
- DICOM-derived patient geometry, where appropriately anonymized and ethically approved.

The major organs included in the simulation are brain, thyroid, lungs, heart, liver, stomach, kidneys, urinary bladder and gonads. Each organ will be assigned an appropriate material composition and density to represent its radiation interaction characteristics.

4. FINDINGS

The proposed Geant4 simulation is expected to provide quantitative information regarding radiation dose distribution in paediatric organs under different CT scanning conditions. The findings will be organized into three main areas.

4.1 Influence of Tube Voltage on Organ Absorbed Dose

The simulation will compare the absorbed dose at 80, 100 and 120 kVp.

4.2 Organ-Specific Radiation Dose Distribution

The simulation will generate three-dimensional dose distributions within the paediatric phantom. The dose maps will help identify organs receiving relatively high radiation exposure and demonstrate the influence of anatomical position on dose distribution. Particular attention will be given to radiosensitive organs, including the thyroid, lungs, stomach, liver and gonads. The analysis will also compare directly irradiated organs with organs receiving radiation through scattered photon interactions.

4.3 Validation of Simulation Results

The Geant4 results should be validated against available experimental measurements or published paediatric phantom dosimetry data. Carver et al. (2015) reported an approximately 6%

overall average difference between their simulated and measured CTDI values, demonstrating the importance of experimental validation. A 2026 study by Attalla et al. also demonstrated the feasibility of comparing simulated organ doses with TLD measurements in paediatric phantoms. The proposed study will use the following validation parameters:

- CTDIvol.
- Dose-length product (DLP).
- Organ absorbed dose.
- Percentage difference between simulation and measurement.
- Monte Carlo statistical uncertainty.

5. DISCUSSION

The application of Geant4 Monte Carlo simulation provides an effective computational approach for investigating radiation exposure in paediatric patients undergoing CT examinations. One important aspect of this study is the consideration of age-specific anatomical characteristics. The radiation absorption and scattering processes in a five-year-old child may differ from those in adult patients because of differences in body dimensions, organ positioning and tissue composition. The use of different tube voltages provides an opportunity to investigate the influence of X-ray energy spectra on organ-specific absorbed doses.

At lower tube voltages, the X-ray spectrum generally contains lower-energy photons, which may increase the contribution of photoelectric interactions. However, the resulting organ dose depends on the complete scanner protocol, including tube current, filtration and photon fluence. At higher tube voltages, photon penetration generally increases. Nevertheless, the total absorbed dose cannot be determined from tube voltage alone because scanner output and exposure settings also influence the radiation delivered to the patient. Another important consideration is the anatomical position of each organ. Organs located within the primary scan region generally receive more direct exposure than organs outside the scan region, although scattered radiation may contribute to their absorbed dose.

The proposed Geant4 framework allows these variations to be investigated through three-dimensional dose mapping. Furthermore, the study may support the development of patient-specific radiation dose estimation. By incorporating patient dimensions, organ masses and scanning parameters, the simulation could provide more representative dose estimates than generic scanner output indicators alone.

However, several limitations must be considered. First, the accuracy of the simulation depends on the quality of the computational phantom and the accuracy of its material composition. Second, the X-ray source spectrum and scanner geometry must represent the actual CT system. Third, sufficient photon histories are necessary to reduce statistical uncertainty. Finally, radiation dose optimization should not compromise diagnostic image quality. Therefore, future studies should incorporate image quality indicators such as image noise, contrast-to-noise ratio and spatial resolution. Overall, Geant4 provides a promising platform for developing a computational decision-support framework for paediatric radiation protection.

6. CONCLUSION

This study proposes a Geant4-based Monte Carlo simulation framework for assessing radiation dose in paediatric patients undergoing CT examinations. The computational approach incorporates a five-year-old anthropomorphic phantom and X-ray spectra corresponding to 80, 100 and 120 kVp to investigate radiation interactions and energy deposition within selected organs. The proposed methodology enables organ-specific absorbed dose estimation, visualization of radiation distribution and comparison of different imaging parameters. The findings are expected to provide valuable information regarding the relationship between X-ray tube voltage and organ radiation exposure in paediatric patients. The integration of Geant4 simulation with appropriate paediatric computational phantoms and experimental validation offers an opportunity to improve radiation dose assessment and support optimized CT imaging protocols. Ultimately, this innovation may contribute to improved patient-specific dosimetry, reduced unnecessary radiation exposure and enhanced radiation protection in paediatric diagnostic imaging.

Acknowledgments: The author would like to thank the Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia for facilities provided that make the research possible.

References

Agostinelli, S., et al. (2003). Geant4—A simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A,* 506(3), 250–303. https://doi.org/10.1016/S0168-9002(03)01368-8

Allison, J., et al. (2006). Geant4 developments and applications. *IEEE Transactions on Nuclear Science*, 53(1), 270–278. https://doi.org/10.1109/TNS.2006.869826

Allison, J., et al. (2016). Recent developments in Geant4. *Nuclear Instruments and Methods in Physics Research Section A*, 835, 186–225. https://doi.org/10.1016/j.nima.2016.06.125

Attalla, E. M., El Gendy, R. A., Abdelbadee, S. A., Mosallam, A. S., et al. (2026). Assessment of radiation doses in computed tomography scans using simulation models versus experimental verification and cancer risk estimation in pediatric phantom. *Egyptian Journal of Radiology and Nuclear Medicine,* 57, Article 55. https://doi.org/10.1186/s43055-026-01715-1

Carver, D. E., Kost, S. D., Fernald, M. J., Lewis, K. G., Fraser, N. D., Pickens, D. R., Price, R. R., & Stabin, M. G. (2015). Development and validation of a GEANT4 radiation transport code for CT dosimetry. *Health Physics,* 108(4), 419–428. https://doi.org/10.1097/HP.0000000000000243

International Commission on Radiological Protection. (2007). The 2007 recommendations of the International Commission on Radiological Protection. *Annals of the ICRP,* 37(2–4), 1–332. https://doi.org/10.1016/j.icrp.2007.10.003

International Commission on Radiological Protection. (2020). Paediatric reference computational phantoms (ICRP Publication 143). *Annals of the ICRP*, 49(2).

International Commission on Radiological Protection. (2024). Paediatric mesh-type reference computational phantoms (ICRP Publication 156). *Annals of the ICRP,* 53(1–2). ICRP Publication 156

Lee, C., Kim, K. P., Long, D. J., & Bolch, W. E. (2012). Organ doses for reference pediatric and adolescent patients undergoing computed tomography estimated by Monte Carlo simulation. *Medical Physics*, 39(4), 2129–2146. https://doi.org/10.1118/1.3693052

Sekkat, H., Khallouqi, A., El Rhazouani, O., & Halimi, A. (2025). Deep learning-based organ dose prediction in pediatric head CT using fully automated tissue segmentation and newly developed voxelized phantoms in GATE/Geant4 simulation toolkit. *Radiation Measurements.* https://doi.org/10.1016/j.radmeas.2025.107597