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Development of Simulation Software for X-Ray imaging Techniques with an Intuitive Graphical Interface for Medical Physics Training

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Abstract

Simulation is a widely used tool in medical physics, enabling a deeper understanding of intrinsic physical phenomena within systems. In medical physics, simulation is considered essential for research and training due to the unique nature of medical physics equipment, such as X-ray imaging, tomography, and radiotherapy devices, which are used for human diagnosis and treatment. Ethical constraints prevent the use of human subjects in experimental research and training, necessitating the use of phantoms that closely mimic human anatomy. However, measurements on phantoms do not fully replicate radiation interactions with human tissue, highlighting the need for simulation combined with experimental measurements to enhance the accuracy and effectiveness of diagnosis and treatment in medical physics. This article presents the development of medical physics simulation software with an intuitive, user-friendly graphical interface. The software supports medical physics engineers in professional training and research, optimizing diagnostic and radiotherapy techniques to improve the quality of patient diagnosis and treatment.

Keywords: Diagnostic imaging, X-ray, simulation software.

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1. Introduction

In the field of medical physics, simulation has established a critical role, particularly in diagnostic and therapeutic applications involving ionizing radiation, such as X-ray imaging, Computed Tomography (CT), radiotherapy, and other imaging techniques. This method enables the modeling of complex interactions between radiation and matter without requiring direct experimentation on human subjects, thereby reducing the risk of radiation exposure and optimizing costs [1]. Numerous research groups have emphasized that simulation facilitates the analysis of physical processes related to dose distribution and image quality, contributing to improved efficacy of medical procedures [2, 3]. Thanks to advancements in Monte Carlo simulation techniques, the ability to predict and refine radiation parameters has significantly improved, laying the foundation for the development of advanced diagnostic and therapeutic methods [4]. In particular, simulation supports in-depth training, providing a virtual practice environment for students, engineers, and researchers without complete reliance on physical equipment.

Globally, advanced simulation tools such as GEANT4 and GATE have been developed and widely applied in medical physics research. GEANT4, a Monte Carlo-based simulation platform, offers detailed modeling of photon and particle interactions, utilized in various applications from X-ray imaging to radiotherapy [5]. Meanwhile, GATE, an extension of GEANT4, is optimized for simulating medical devices such as CT scanners and linear accelerators, achieving high accuracy in analyzing radiation spectra and dose distribution, as reported by Jan and colleagues [3]. However, in Vietnam, despite certain advancements in medical physics, the development of specialized simulation software, particularly those integrating physical parameters and reconstructing images from radiation imaging processes in devices like CT and X-ray systems, remains limited. The absence of domestically developed tools has hindered the effectiveness of training and practical applications, especially given the modest technological resources available.

Given this context, this study proposes the development of a simulation software for medical physics in Vietnam, enabling the configuration of physical parameters involved in radiation-based image formation to reconstruct images, with faster processing speeds compared to specialized simulation software such as GEANT4 and GATE, making it more suitable for training purposes. The software's output data is based on a simulation library created by the research team using GATE, enhancing accuracy while minimizing execution time for users. The primary objective is to develop a tool with an intuitive graphical interface, easy to operate, offering advantages such as faster processing speeds and clear visualization for students during teaching, compared to simulations using GATE or GEANT4.

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2. Objects and Methods

The study focuses on developing specialized simulation software for medical physics in Vietnam, aimed at enhancing training efficiency through image reconstruction based on the physical parameters of radiation-based image formation. The software allows users to customize parameters such as high-voltage settings (kV), filter configuration (material and thickness), current intensity (mA), geometric configuration (distance from the X-ray source to the detector; distance from the X-ray source to the imaging object), and selection from three standard phantoms in the simulation (simple cylindrical phantom, voxel phantom derived from CT scans, and International Commission on Radiological Protection (ICRP) tetrahedral phantom). The foundational data is built from pre-simulated scenarios using GATE, stored in a reference library to ensure significantly faster processing speeds compared to tools like GEANT4 and GATE, which typically require hours to days for computation [5, 6].

2.1. Design and Development the Software

The software is designed with modular architecture, utilizing the Python programming language to ensure flexibility and high performance. The graphical interface is developed with input components such as sliders and dropdown menus, allowing users to adjust physical parameters: high-voltage settings (kV) from 40 to 150 kV, filter configuration with default materials and varying thicknesses, current intensity (mAs) from 1 to 500 mAs, geometric configuration (distances from 50 to 150 cm), and selection of different phantom types. Data processing is performed using a fast lookup algorithm based on a data library, instead of direct Monte Carlo calculations, reducing processing time to a few seconds or minutes. The software's block diagram is presented in Fig 1.

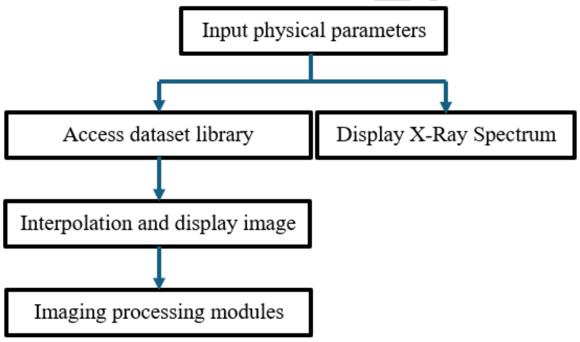

Fig. 1. The block diagram of the software

2.2. Calculation of X-Ray Spectrum

The X-ray radiation spectrum consists of two components: the bremsstrahlung spectrum and the characteristic X-ray spectrum. The bremsstrahlung spectrum is described by the formula:

$$I_0(E) \approx Z\frac{E_{max}-E}{E} \quad (1)$$

where $I_0(E)$ is bremsstrahlung radiation intensity at energy (E), E_{max} denoting the maximum acceleration energy of the electron beam, and Z indicating the atomic number of the target material.

The characteristic X-ray spectrum depends on the target material. For example, with a tungsten target, four characteristic peaks appear at 57.9 keV, 59.3 keV, 67.2 keV, and 69.1 keV. These monoenergetic peaks are broadened using a Gaussian distribution to obtain energy peaks that align with experimental observations. This approach supports spectroscopic X-ray imaging by preserving energy-resolved information, which can enhance material discrimination and reduce beam-hardening artifacts in diagnostic applications [6].

The above formulas are applied to the theoretical case of X-Ray spectrum (unshielded X-ray radiation). In practice, the X-ray beam emitted from the target passes through the insulating oil layer in the tube, the glass envelope of the tube, and the exit window for the X-ray. The materials comprised of the X-ray tube create an inherent shielding layer for the X-ray generator. The intensity of the X-ray beam after passing through these shielding layers is calculated using the Beer-Lambert formula as follows:

$$I(E) = I_0(E)e^{-\mu(E)t} \quad (2)$$

where $I(E)$ denoting the beam intensity after passing through the shielding layer, $\mu(E)$ indicating the energy-dependent attenuation coefficient of the X-ray beam as it passes through the shield, and t is the thickness of the shielding layer.

For simplicity, the shielding materials are converted to an equivalent aluminum layer, with the inherent shielding of the X-ray generator corresponding to 2.5 mm of aluminum (users can add additional shielding thickness to simulate various physical effects of the X-ray beam). The energy-dependent linear attenuation coefficient data is sourced from the National Institute of Standards and Technology (NIST).

2.3. Building a Data Library from GATE Simulation

The data library was constructed through detailed simulations using GATE software, an open-source Monte Carlo platform extended from GEANT4, calibrated based on published experimental data. This process includes:

1. Defining simulation scenarios with combinations of physical parameters (voltage, filtration, intensity, etc.) and phantom configurations;
2. Setting up the geometric model in GATE based on simulation configuration macros, with the

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X-ray energy spectrum used for GATE simulations derived from the calculations described above;

3. Running GATE with various configurations and different numbers of event generations to produce multiple images with varying quality and parameters, suitable for subsequent interpolation;
4. Storing the results in a digitized file format to optimize data retrieval.

The use of the data library for interpolating image results ensures high accuracy [5] and reduces processing time from hours or days (typical of GEANT4 and GATE) to just a few minutes. By expanding the simulations and potentially integrating with real-world data, the simulation scenarios can be extended indefinitely, allowing the software's functionality to approach that of actual X-ray imaging software.

The integration process employs a multilinear interpolation algorithm to map parameters into the library data. After the user selects the parameters, the software reconstructs 2D or 3D images, reflecting physical characteristics such as contrast and noise, based on the GATE simulation data. The results are validated by comparing them with GATE simulations on a test dataset, ensuring reliability and applicability in line with medical simulation standards [4].

2.4. Setup Simulation Parameters and Configuration

To ensure the simulation aligns with real-world imaging conditions, determining the configuration and setting simulation parameters are critically important. As directly simulating the X-ray spectrum is complex and time-consuming, in this study, we will not simulate the X-ray generation process. Instead, the X-ray spectrum used for simulation will be generated based on the computational technique for X-ray spectrum calculation described in Section 2.2. The X-ray spectrum generated from the computational program will be declared as the source file for the GATE simulation program. The simulation configuration will be selected to match the actual imaging setup: the distance from the source to the detector is set at 125 cm, with the detector placed close to the phantom. Additionally, users can adjust the source-to-detector and detector-to-phantom distances to investigate different imaging conditions. The Monte Carlo simulation method performs random calculations by generating events, thereby calculating interaction probabilities. The resulting output is a probability distribution, which does not directly correlate with the attenuation obtained in real X-ray imaging. However, this probability distribution is proportional to the X-ray imaging dose. Therefore, the actual imaging dose can be simulated by varying the number of histories in the simulation. The relationship between the number of histories and the imaging dose will be determined by simulating a phantom used to evaluate diagnostic imaging quality. The simulated phantom image with *n* histories will be considered equivalent to the actual phantom image at dose A if the contrast-to-noise ratio (CNR) of the two images is comparable. However, since the imaging dose is a function of beam intensity and energy, we first need to establish the relationship between the number of histories and beam intensity at a fixed tube voltage by plotting a curve describing the relationship between CNR, the number of histories, and the tube current at a constant voltage. Subsequently, an empirical formula will be used to determine the required number of histories when varying the tube voltage, based on the empirical relationship between tube voltage and tube current [7]:

$$\left(\frac{kVp_1}{kVp_2}\right)^5 = \frac{mAs_2}{mAs_1} \tag{3}$$

where kVp is the X-ray tube voltage, and mAs is the tube current-time product.

2.5. Evaluation of Software Performance

The software's effectiveness was assessed based on three main criteria: (1) Processing time, compared with GEANT4 and GATE for the same scenarios as conducted by Jan and colleagues [3]; (2) Accuracy of reconstructed images, measured by the Peak Signal-to-Noise Ratio (PSNR) against experimental and GATE simulation data; (3) Ease of use in teaching, evaluated through feedback surveys from 50 students and 10 lecturers at Hanoi University of Science and Technology. The tests were conducted using standard scenarios, such as chest X-ray imaging with phantoms, following IAEA guidelines

3. Results and Discussion

3.1. Results

Fig. 2a shows the X-ray spectrum results for various high-voltage settings, generated by the software with an inherent filter thickness of 2.5 mm aluminum. Fig. 2b shows the X-ray spectrum simulated by Monte Carlo simulation with similar conditions. From Fig. 2, it can be observed that the calculated X-ray spectrum in the software is fully consistent with the results obtained from Monte Carlo simulation. The advantage of the spectrum calculation method is its significantly faster computation time compared to simulation (the time to calculate the spectrum is negligible compared to the time required to simulate an X-ray spectrum). Users can quickly set parameters such as tube voltage, effective filter thickness, and target material to generate the corresponding X-ray spectrum. The generated X-ray spectrum serves a dual purpose: it allows users to observe the characteristic shape of the X-ray radiation spectrum and is used as input for the GATE simulation program.

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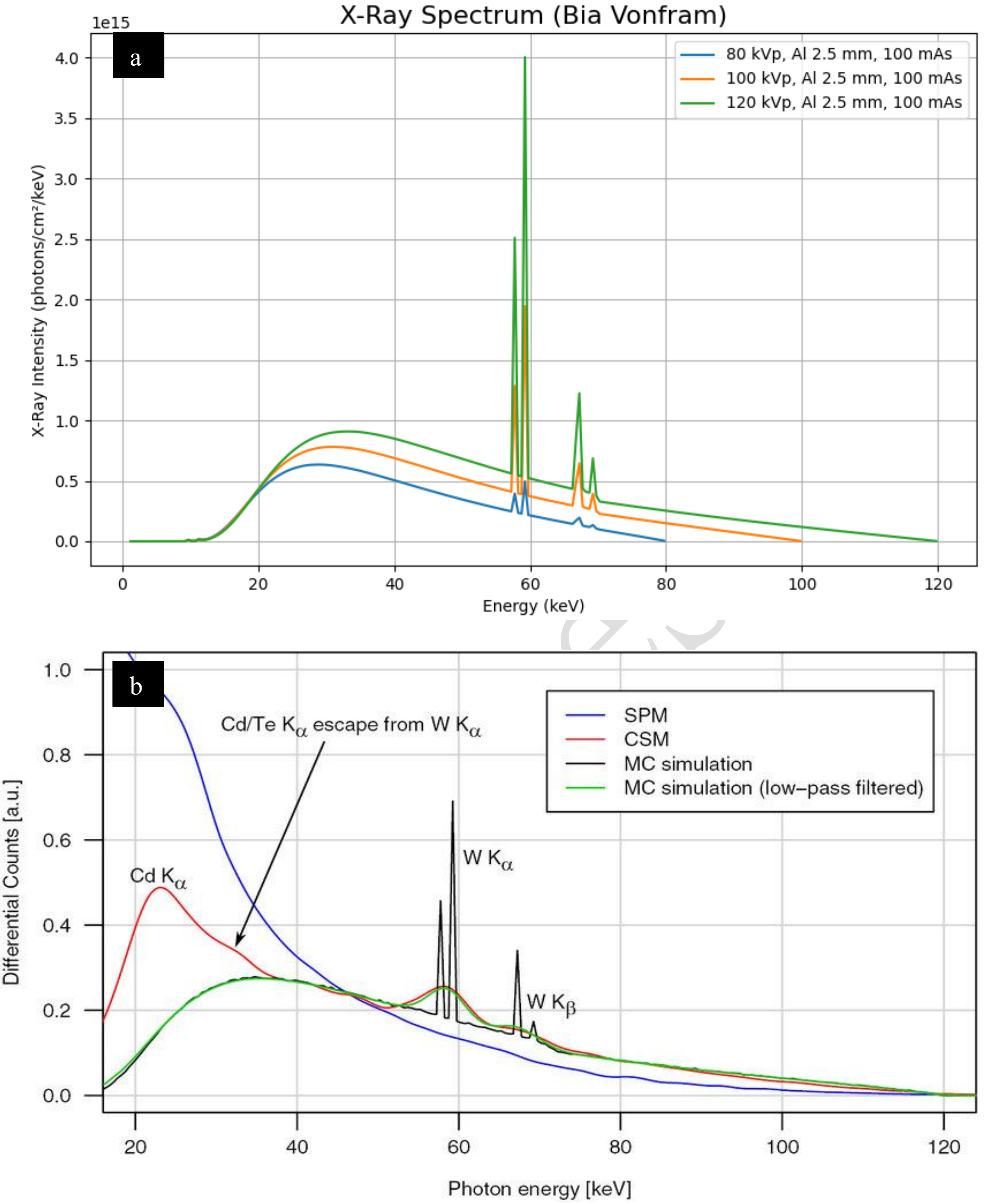

Fig. 2. Results of calculated X-ray spectra: (a) by our analytical method and (b) by Monte Carlo simulation [7]

Fig. 3 illustrates the relationship between the number of simulated events and the X-ray tube current, resulting in images with the same CNR. From the graph, we can derive a formula to determine the number of simulation histories corresponding to the X-ray tube current value, ensuring images of equivalent quality, as given by the formula:

$$Histories = \frac{mAs - 3.3549}{2 \times 10^{-8}} \quad (4)$$

For each change in tube voltage (kVp), (3) is used to determine the corresponding tube current (mAs). Subsequently, (4) is applied to interpolate the required number of simulation histories.

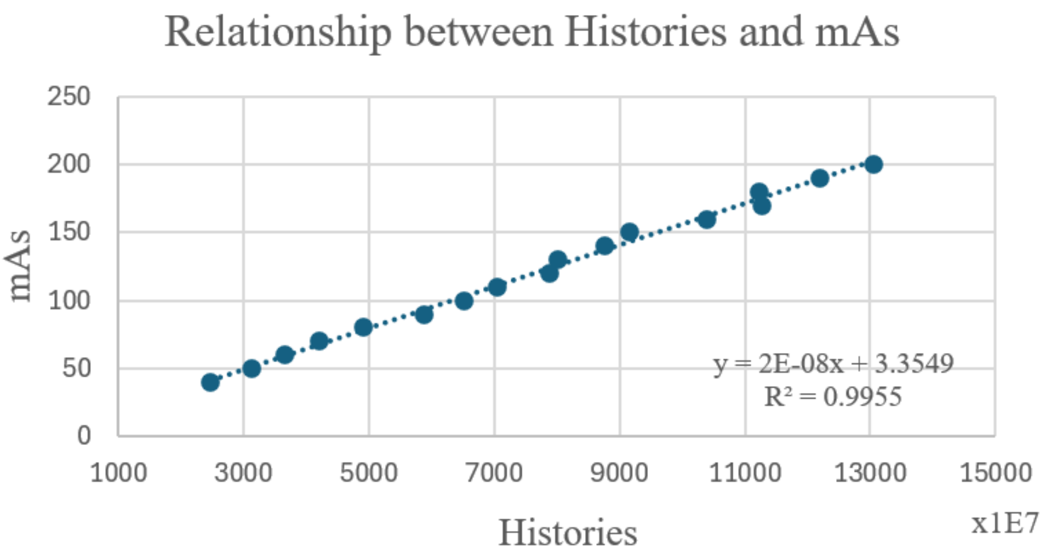

Fig. 3. The relationship between Histories and mAs

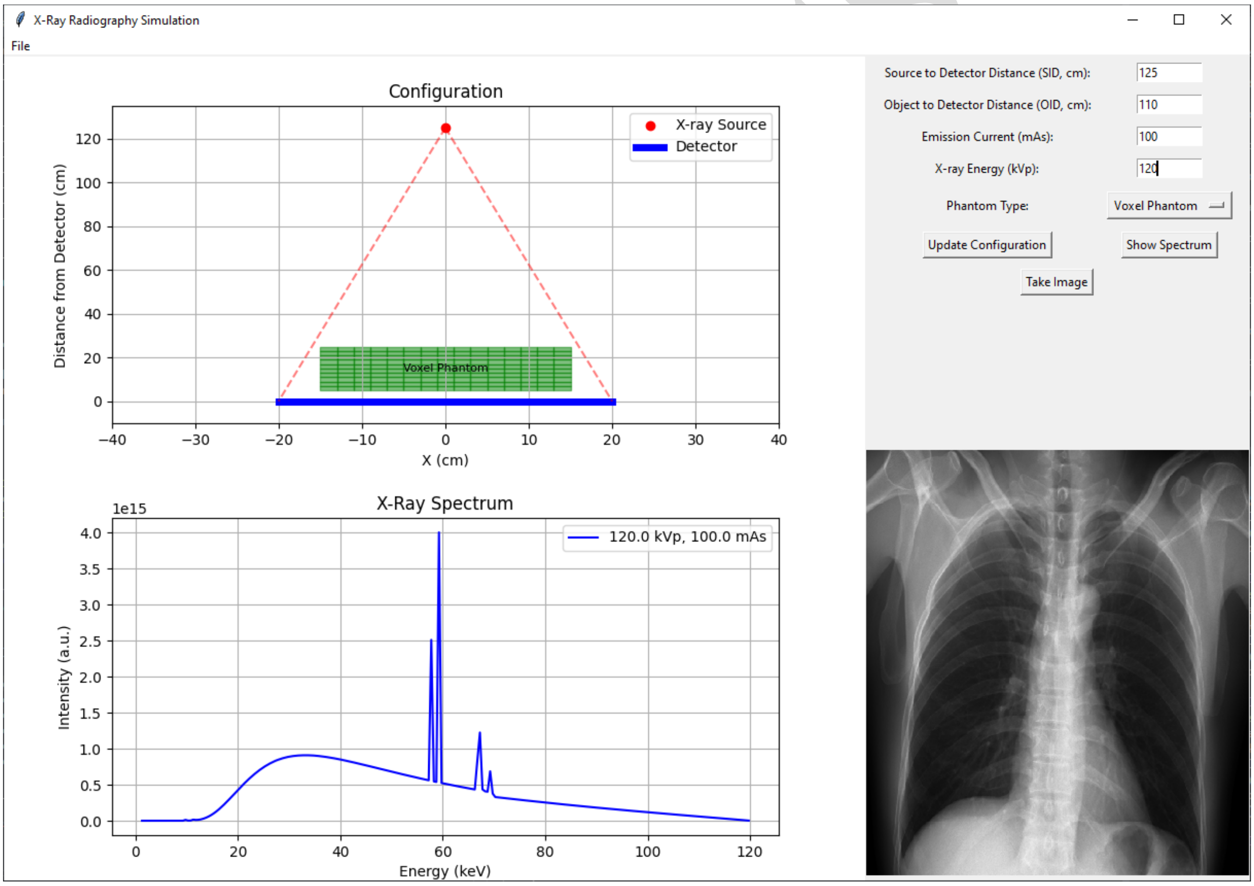

Fig 4. Graphical user interface of the simulation software

Fig. 4 illustrates the software interface for simulating X-ray imaging, featuring adjustable imaging configuration settings, display of X-ray spectra at different energy levels, and simulated images corresponding to the selected phantom type.

Fig. 5 presents the X-ray images obtained from the software at a high voltage setting of 120 kV, with X-ray tube currents selected at 100 mAs, 80 mAs, 60 mAs, and 40 mAs.

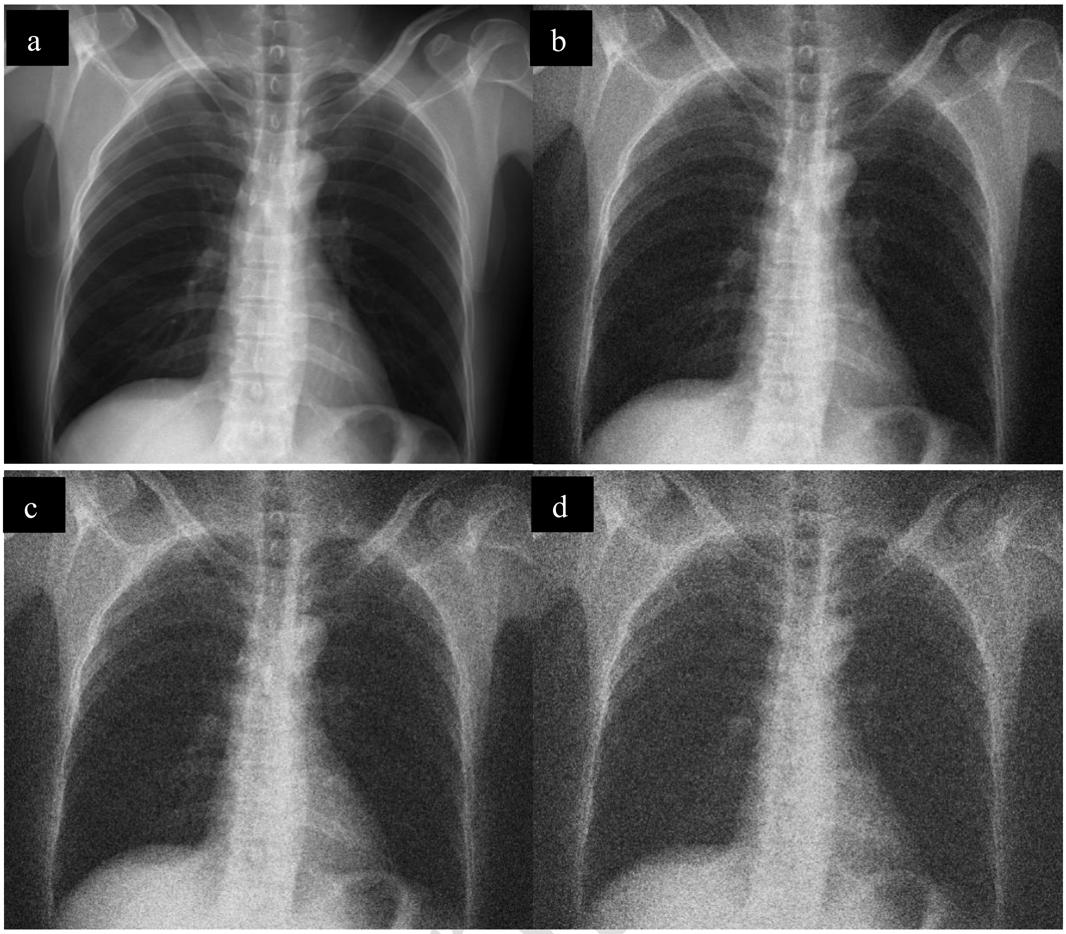

Fig 5. Simulated chest X-ray images with different X-ray tube currents: a) 100 mAs; b) 80 mAs; c) 60 mAs, and d) 40 mAs

Table 1 presents the peak signal-to-noise ratio (PSNR) values of the images obtained from the simulation software at tube current-time product values of 40 mAs, 60 mAs, 80 mAs, and 100 mAs.

Table 1. PSNR values of bone at different mAs

	100 mAs	80 mAs	60 mAs	40 mAs
PSNR (Our)	38 dB	27 dB	15 dB	11 dB
PSNR (GATE)	40 dB	31 dB	19 dB	12 dB

3.2. Discussion

The software implementation results demonstrate an intuitive graphical interface, successfully reconstructing 2D projection images from input physical parameters. The reconstructed images accurately reflect physical characteristics such as contrast and noise, with an average processing time ranging from 2 to 5 seconds across different configurations. Compared to direct GATE simulations, which require 6–48 hours [3], the software exhibits superior performance, making it particularly suitable for educational purposes. Image quality remained stable across standard scenarios, confirming its practical applicability.

From Fig. 3, it can be observed that the calculated X-ray radiation spectrum from the software closely matches results published by international research groups using similar methods, as well as experimental measurements. By adjusting the thickness of the beam filter, users can visually observe changes in the X-ray spectrum and its impact on the quality of the resulting X-ray images. This report focuses on calculating the X-ray spectrum for a tungsten target, but extending the calculation to other target materials is straightforward. Fig. 4 illustrates the image quality generated by the software at different radiation dose levels. These images were produced by varying the number of simulated events in GATE, creating a dataset of images with different statistical errors. Visually, as the X-ray tube current decreases, the images become increasingly noisy. The average PSNR values decrease from 38 dB, 27 dB, and 15 dB, to 11 dB for images a, b, c, and d, respectively. Notably, the PSNR does not decrease linearly with the reduction in tube current. This is attributed to the limited number of simulation data points, leading to inaccuracies in interpolation, as well as challenges in accurately correlating the number of simulated events with radiation dose, which affects the result's precision.

The software achieves a processing speed approximately 10.000–30.000 times faster than GEANT4 and GATE in standard scenarios (voxel phantom, 120 kV, 2.5 mm aluminum filter). However, the average PSNR of 35 dB is slightly lower than GATE's 40 dB due to limitations in the interpolation algorithm [5]. This difference has minimal impact on the educational objective, which prioritizes concept illustration. Although the software's interface is relatively simple, it is significantly more user-friendly than open-source tools globally, which require advanced technical skills to operate, highlighting its superiority in educational settings.

A preliminary internal feedback collection from 50 students and 10 lecturers at Hanoi University of Science and Technology indicated positive perceptions regarding the software's user-friendliness and educational value. The software helped enhancing understanding of medical physics for students. The feedback analysis showed that 85% of students rated the interface as easy to use, while 90% noted that the configuration and physical parameters of X-ray techniques were illustrated more clearly than with GEANT4 or GATE.

The software marks a pioneering contribution in Vietnam by developing the first simulation tool utilizing a GATE data library for image reconstruction in medical physics training at Hanoi University of Science and Technology. Compared to international tools, the software stands out due to its optimized processing time and user-friendly interface design, meeting the needs of educational institutions with limited resources. Its novelty lies in the use of pre-processed data, reducing reliance on complex computational infrastructure and laying the foundation for domestic development. The main limitation of the software is reduced accuracy for scenarios beyond the current data library's scope, due to its dependence on pre-processed GATE data. This suggests the need to expand the library with more diverse configurations in the future. Additionally, the software does not yet support real-time simulation for continuous parameter changes, an aspect that could be improved with additional optimization algorithms. Compared to international studies, this approach is not yet widely adopted, but its potential in resource-constrained countries like Vietnam is significant, opening prospects for international collaboration to develop training software for medical physics and nuclear engineering.

4. Conclusions

Through this research, the team successfully developed simulation software for X-ray imaging techniques tailored for medical physics training. The software utilizes physical and pre-simulated data to generate X-ray images for various phantom types. It also calculates physical parameters of the X-ray beam, such as the X-ray spectrum and the impact of beam filtration, while visually displaying the spectrum for easy user observation. By employing interpolation from pre-existing data, the software achieves significantly faster simulation speeds compared to direct Monte Carlo methods. However, the results exhibit some inaccuracies due to the limited amount of simulation data, leading to suboptimal interpolation. This necessitates expanding the dataset and developing better interpolation techniques. The X-ray simulation software is still in the refinement stage. Due to the lengthy simulation times, the research team has so far only demonstrated results related to changes in image quality with varying X-ray tube currents. Other physical parameters, such as the impact of high voltage on contrast and the effects of beam hardening, will be fully implemented in the next phase. With a sufficient dataset, instead of conventional interpolation, the software could incorporate deep learning models (trained on simulated and real data) to infer X-ray images from input physical parameters. The simulation software, with its innovative approach, is particularly valuable for medical physics training in Vietnam, where training facilities often lack sufficient equipment. The concept behind the software can be extended to simulate other diagnostic imaging techniques, such as CT, Single Photon Emission Computed Tomography (SPECT), and Positron Emission Tomography (PET), providing significant practical and educational value for students.

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