JOINT INSTITUTE FOR NUCLEAR RESEARCH
Laboratory of Nuclear Problems

FINAL REPORT ON THE INTEREST PROGRAMME

“Monte Carlo simulation of radiation-matter interaction for shielding evaluation in medical imaging applications”

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Participation period:
February 24 - April 14, 2024
Wave 10

Dubna, 2024

Abstract

Monte Carlo simulations have become an indispensable tool in the field of radiation shielding design, particularly in the context of preclinical SPECT/CT scanning applications where precise assessment of radiation exposure is crucial. This study presents a Monte Carlo simulation tool called MCNP tailored for evaluating radiation-matter interactions. The simulation incorporates detailed models of radiation sources commonly used in medical imaging, such as X-ray tubes and radioactive isotopes. Various lead shielding thicknesses are assessed for their effectiveness in attenuating radiation doses in simulated scenarios resembling clinical settings. Results demonstrate the utility of Monte Carlo simulations in optimizing radiation-shielding designs for medical imaging facilities, offering insights for enhancing radiation protection for both patients and medical personnel. This work contributes to the advancement of safety protocols in medical imaging, facilitating the development of more efficient and robust shielding solutions.

Keywords: single photon emission tomography, Monte Carlo N-Particle Transport code, dose rate, computed tomography.

Introduction

The first and revolutionary use of radiation in medicine occurred over a hundred years ago when Wilhelm Roentgen discovered X-rays. This discovery initiated many new methods of examining the human body, including computed tomography. Godfrey Hounsfield and Allan Cormack proposed this method in 1972, for which they later received the Nobel Prize. It is based on the measurement and sophisticated computer processing of the difference in attenuation of X-rays by different tissue densities. Currently, X-ray computed tomography is the main tomographic method of analyzing human internal organs using X-rays.

Another method of analyzing the human body is Single Photon Emission Computed Tomography (SPECT), which is a diagnostic method of creating tomographic images of radionuclide distribution. SPECT uses radiopharmaceuticals labeled with radioisotopes whose nuclei emit only one gamma quantum (photon) during each act of radioactive decay.

However, the best efficacy in patient examination is achieved when both of these methods are combined. Despite the advantages of this approach, there is one significant disadvantage - it involves an increase in absorbed radiation for both patient and staff due to scattered radiation. This is why there is a need to protect the working staff from radiation as well as carefully selecting the dose to the patient.

Project Goals:

- Review the mechanism of interaction radiation with matter
- Familiarization with the methods CT and SPECT scanning
- Study of MCNPX software package for Monte Carlo simulations
- Calculation of dose rate behavior with the distance to the source and thickness of lead shielding

1. Materials and Methods.

1.1. SPECT/CT tomography.

1.1.1. CT

CT-scan (computed tomography scan) is a medical imaging technique used to obtain detailed internal images of the body [1]. It combines a series of X-ray images taken from different angles around your body and uses computer processing to create cross-sectional images. By stacking the obtained layers, it is possible to get a 3D model of a man.

The main part of any modern CT scanner is the gantry - a ring inside which the beam tube rotates rapidly, opposite to which the transducers are located. The patient lies down on a moving table that moves inside this ring. The movement of the table and the X-ray tube are synchronized so that the resulting reading is performed in a spiral that circles the patient's body in the area of the part to be examined from all sides (multislice CT scanning in Fig.1).

In addition, CT scan can be used in patients with metallic implants or pacemakers, for whom magnetic resonance imaging is contraindicated [1].

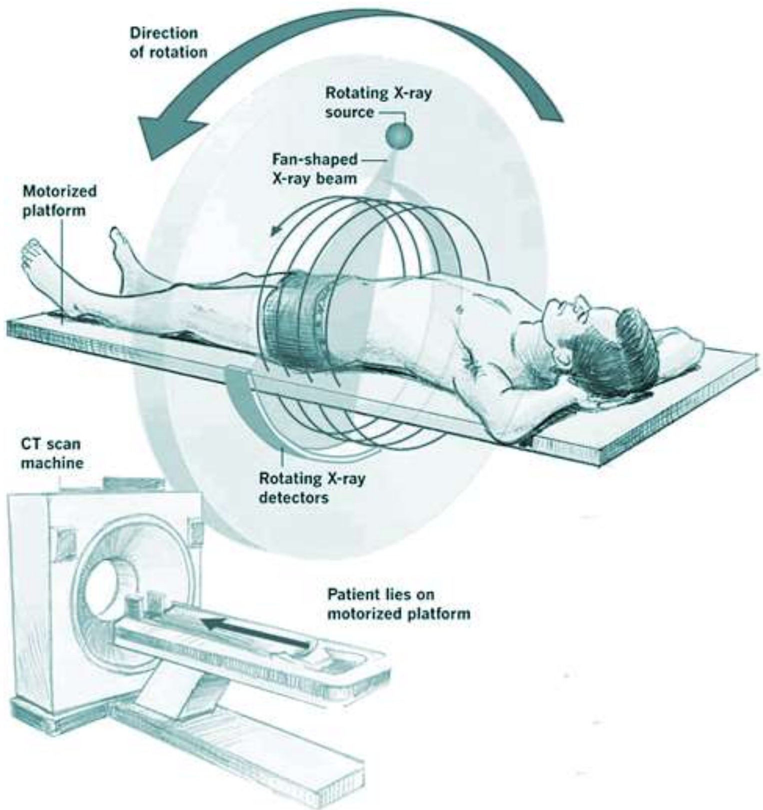


Fig. 1. A MSCT scan scheme [2].

Although CT scanning machines come in different varieties, the following basic components are always retained:

- Gantry - the ring-shaped part of the scanner that houses the x-ray tube, detector array, and other components. During scanning, the Gantry rotates around the patient, thereby changing the angle of incidence of radiation.
- Beam detectors;
- Detectors to receive the reflected beam;
- Detector motion system;
- X-ray beam converters and its transformation into geometric digital signals;
- A computing unit that calculates the characteristics of the rays and transformed signals in order to format the best quality image and calculate its resolution;
- Software, peripheral devices for image processing, translation, reproduction, and recording.

After the object scanning and the signal computer processing, a graphic image of the slice is reconstructed. In this case, each cell of the matrix corresponds to a computer-calculated tissue absorption coefficient (CA) in Hounsfield units. The CA is similar in meaning to the degree of blackening of the radiograph, i.e., it shows how much the tissue is able to absorb X-rays. Bone absorbs X-rays more strongly than other tissues and has the highest CA. Air practically does not absorb and has the lowest CA. The CA of water is taken as zero.

For material X with a linear attenuation coefficient μ_x the HU, value is determined by the formula [3]:

$$HU = \frac{\mu_x - \mu_{water}}{\mu_{water} - \mu_{air}} \times 1000 ,$$

where μ_{water} and μ_{air} are the linear attenuation coefficient of water and air respectively.

The approximate X-ray densities for various tissues are listed below:

- Air: -1000 HU.
- Respiratory organs: -950 to -300 HU.
- Blood (without vascular contrast): 0 to 100 HU.
- Bones: 100 to 1000 HU.

1.1.2. SPECT

Single-photon emission computed tomography (SPECT) is a diagnostic method of creating tomographic images of radionuclide distribution. SPECT uses radiopharmaceuticals labeled with radioisotopes whose nuclei emit only one gamma-quantum (photon) during each act of radioactive decay (for comparison, PET uses radioisotopes emitting positrons).

The test is performed by injecting a microscopic amount of labeled isotopes emitting single photons into the patient's body. Subsequent scanning makes it possible to detect the areas of greatest accumulation of isotopes, to analyze them structurally, and thus to detect dangerous diseases at early stages, before the appearance of clinical symptoms.

In order to obtain SPECT images, the gamma camera is rotated around the patient. Projections are captured, usually every 3 to 6 degrees. In most cases, a full 360-degree rotation is used to obtain optimal recovery (Fig. 2). The typical time required to obtain each projection is 15-20 seconds. Correspondingly, the total scan time is 15-20 minutes. To reduce scanning time, detection systems consisting of two or more gamma cameras are used.

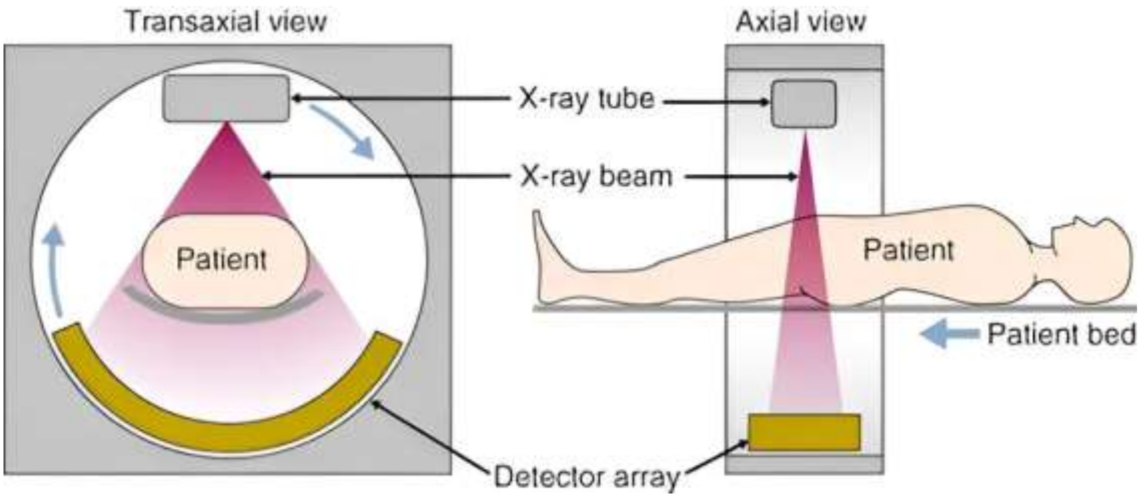


Fig. 2. Schematic representation of SPECT scanner [4].

The use of electrocardiograph as a trigger in SPECT allows obtaining differential information about the heart work at different moments of the cardiac cycle.

Scintigraphy and SPECT use the same radioactive drugs. Most diagnostic procedures (~80%) over the last 30 years have used ^{99m}Tc preparations, which emits photons with energy 140 keV (Fig. 3). However, other radioisotopes are also used. The table summarizes some of the isotopes used in diagnostics.

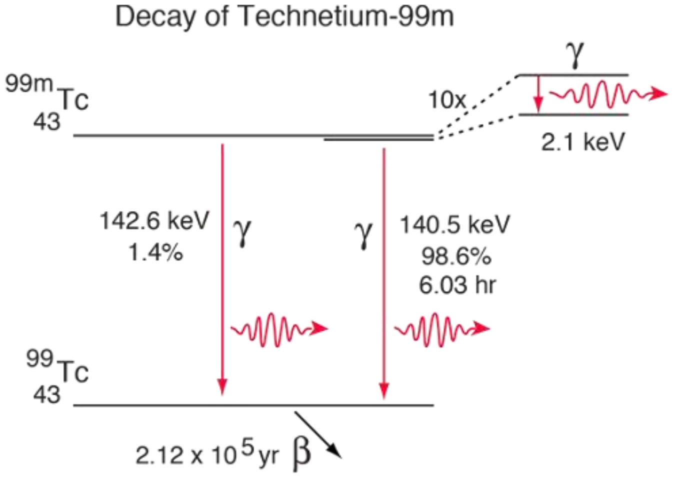


Fig. 3. Technetium-99m decay scheme [5].

Table 1. Commonly used SPECT radioisotopes.

Element	Half-life, hours	Emission energy, keV
^{99m}Tc	6	140
^{201}Th	73	72
^{123}I	13,2	159
^{131}I	~192	364

1.1.3. SPECT-CT

SPECT/CT is a technology that seamlessly combines the functional sensitivity of SPECT with the high anatomical detail of multislice CT. This combination provides excellent image quality, allowing for precise localization of lesions. SPECT/CT provides simultaneous acquisition of diagnostic information for both types of studies. This results in increased accuracy of both types of examinations. As a result, doctors can draw conclusions much more confidently than before. The precise combination of anatomical and functional images increases the reliability of lesion detection and localization.

With the ability to perform two optimized scans during the study, SPECT/CT takes efficiency to an unmatched level while producing the highest quality images. The use of this technique in oncology allows for a more reliable determination of the presence or absence of disease, as well as its severity. The addition of multislice CT provides valuable anatomical information necessary for precise localization of the pathological process.

SPECT/CT is ideally suited for tumor imaging tasks, such as studies of patients with metastatic breast or prostate cancer, primary bone cancer, neuroendocrine tumors, parathyroid adenomas, neuromas, neuroblastomas, multiple myeloma, or liver cancer. In addition, CT data allow correction for tissue attenuation, which makes quantitative analysis of SPECT results possible. Quantitative assessment of radiopharmaceutical accumulation during SPECT helps to improve tumor staging and therapeutic planning.

The integration of SPECT with CT provides physicians with new opportunities for coronary artery disease risk assessment. This new technology provides the ability to quantify coronary artery calcification, determine vessel patency, and measure myocardial perfusion and viability with a single combined system. Recent research and the rapid development of cardiac and vascular computed tomography have demonstrated the enormous potential of this technique. With a fully integrated multislice CT system, a detailed radiation attenuation map is obtained with a scan time of no more than 30 seconds. This method guarantees accurate correction of the emission images and a corresponding improvement in image quality. The joint viewing of examination results obtained simultaneously with complementary imaging devices increases the reliability of diagnosis.

1.1.4. Sources used in SPECT/CT.

The source of X-ray in CT tomography systems is Roentgen tube (schema in Figure 4). In simulations, for the CT configuration, the W anode in the X-ray tube was approximated to a point-like source positioned 1 mm in front of a hypothetical tungsten anode. This source emits only in the phantom direction within a solid angle 20^o. The full X-ray tube energy spectrum was considered in the simulation, and it was calculated using interpolating polynomials (TASMIP) for 120 keV [6].

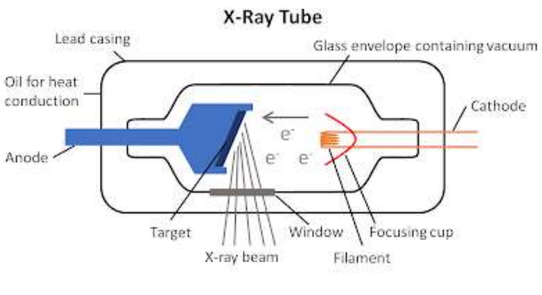


Fig. 4. Production of X-Rays in a Roentgen tube [7].

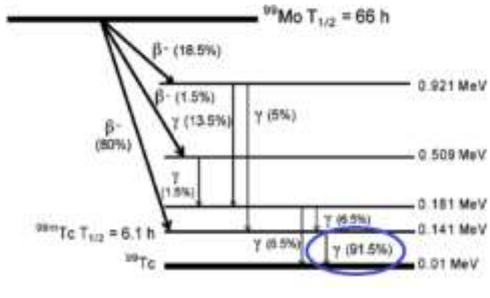


Fig. 5. Molybdenum decay [8].

The gamma radioisotope source, which is injected into the animal under study in the SPECT technique, has been conceived in simulation as a point-like source with photons emitted isotropically. It is positioned in the center of mouse phantom (coordinate center). The energy of the gamma source is selected depending on the isotope to be used, and the activity was taken 10 MBq. Figure 5, as an example, shows the decay scheme of ^{99}Mo, the precursor of ^{99m}Tc.

1.2. Dose safe limits.

The International Commission on Radiological Protection (ICRP) recommends dose limits**.** They are in place to ensure that individuals are not exposed to an unnecessarily high amount of ionizing radiation. Dose limits are a fundamental component of radiation protection, and breaching these limits is against radiation regulation in most countries.

The limits are split into two groups, the public, and occupationally exposed workers [9, 10]. The dose limit for workers proposed by the ICRP was established as an annual effective dose. As presented in Table 2, an effective dose limit of 20 mSv/year has been set for persons employed in radiation work.

Table 2. Dose limits established for occupationally exposed workers and public.

	Effective dose	**Equivalent dose to the lens of the eye**	**Equivalent dose to the skin** (averaged over 1 cm^2)	**Equivalent dose to the hands and feet**
Occupationally exposed workers	20 mSv a year, averaged over defined periods of 5 years with no single year >50 mSv	20 mSv a year, averaged over defined periods of 5 years with no single year >50 mSv [2]	500 mSv a year	500 mSv a year
Public	1 mSv a year (higher values are permitted if the average over 5 years is not above 1 mSv a year)	15 mSv a year	50 mSv a year	-

1.3. *Interaction of photons with matter.*

Like charged particles, the photon flux is absorbed by matter mainly due to electromagnetic interaction. However, the mechanism of this absorption is significantly different. There are two reasons for this:

- Photons have no electric charge and, therefore, are not affected by long-range Coulomb forces. Therefore, when passing through matter, photons relatively rarely collide with electrons and nuclei, but when they do, as a rule, they are sharply deflected from their path, i.e., they are practically eliminated from the beam;
- Photons have zero mass and, therefore, cannot have a speed different from the speed of light. This means that they cannot slowdown in the medium. They are either absorbed or scattered, and mostly at large angles. When a beam of photons passes through matter because of interactions with the medium, the intensity of the beam is gradually weakened.

Main mechanisms of interaction of photons with matter (Fig. 6):

- Photoelectric absorption
- Compton scattering
- Pair production
- Rayleigh scattering

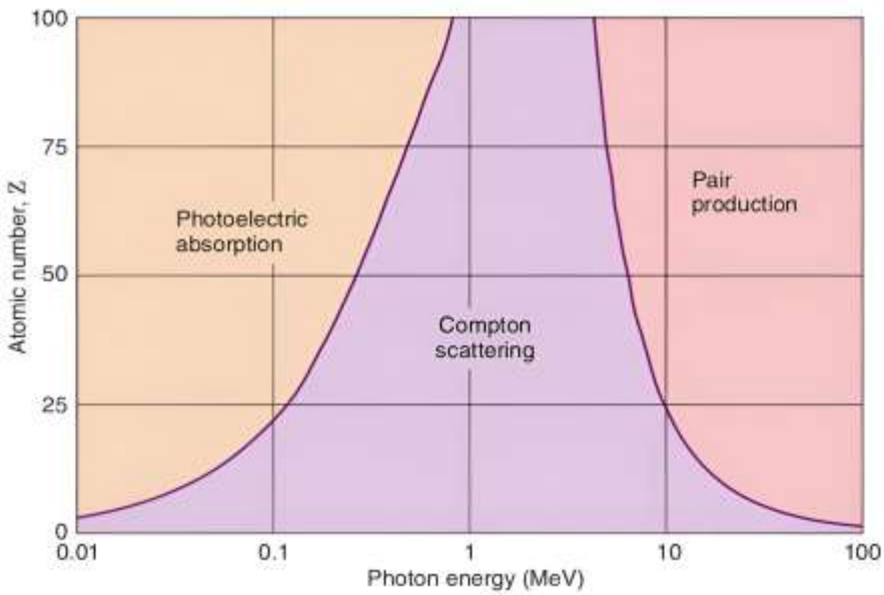


Fig. 6. Main photon interactions versus photon energies for different atomic number [11].

1.3.1. Photoelectric absorption

The photoelectric effect is one of the principal forms of interaction of x-ray and gamma photons with matter. A photon interacts with the inner shell electron of the atom and removes it from its shell (Fig. 7).

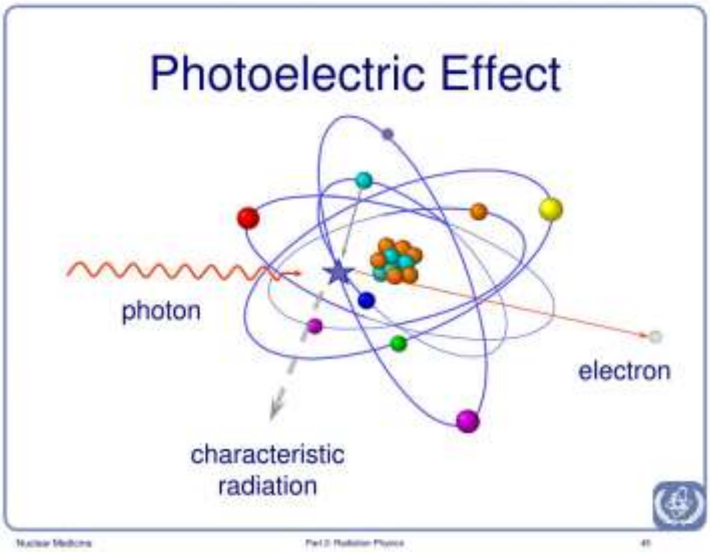


Fig. 7. Schematic of the photoelectric effect.

1.3.2. Compton scattering

Another process of interaction of photons with matter is the so-called Compton scattering. This is the most common mechanism for the interaction of gamma rays with matter.

When a high frequency photon scatters due to an interaction with a charged particle, there is a decrease in the energy of the photon (Fig. 8). Because of conservation of energy the lost energy from the photon is transferred to the recoiling particle (such an electron would be called a "Compton Recoil electron") [12].

- The effect is the elastic scattering of a photon on an electron. The angle of scattering of the photon can be any angle.
- To find the energy of the scattered photon it is enough to use the formula:

$$h\nu' = h\nu \frac{1}{1+\alpha(1-\cos\theta)},$$

where $\alpha = \frac{h\nu}{m_0 c^2}$, h is the Planck constant, ν is the incident photon frequency, ν' is the scattered photon frequency and θ is the angle of the scattered photon.

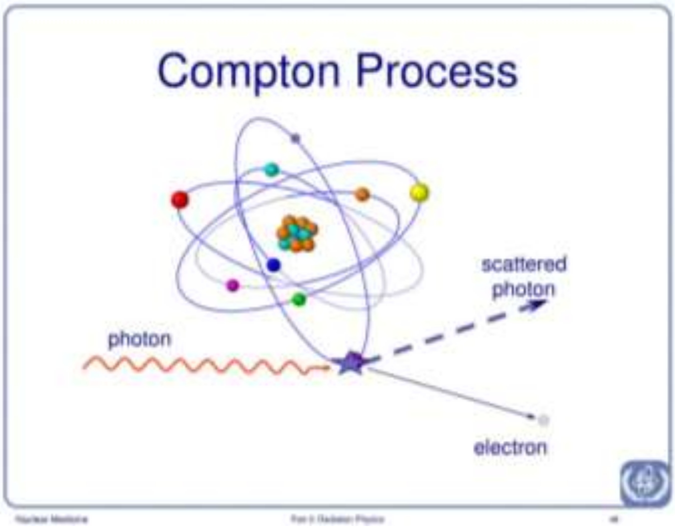


Fig. 8. Schematic of the Compton scattering.

1.3.3. Pair production

As the photon interacts with the strong electric field around the nucleus, it undergoes a change of state and is transformed into two particles: one electron and one positron (Fig. 9). This is essentially creating matter from energy. This process only occurs when the incident photon energy is at least 1.022 MeV.

- In the case of a photon that interacts with matter, having an energy greater than 1.022 MeV it can annihilate into a so-called electron-positron pair. It is also worth noting that this pair of particles does not scatter on orbiting electrons.
- The kinetic energy of the electrons produced will be the difference between the energy of the incoming photon and the energy equivalent of two electron masses
- Pair production probability increases with atomic number as Z^2

$$E_{e+} + E_{e-} = h\nu - 1.022\ (MeV)$$

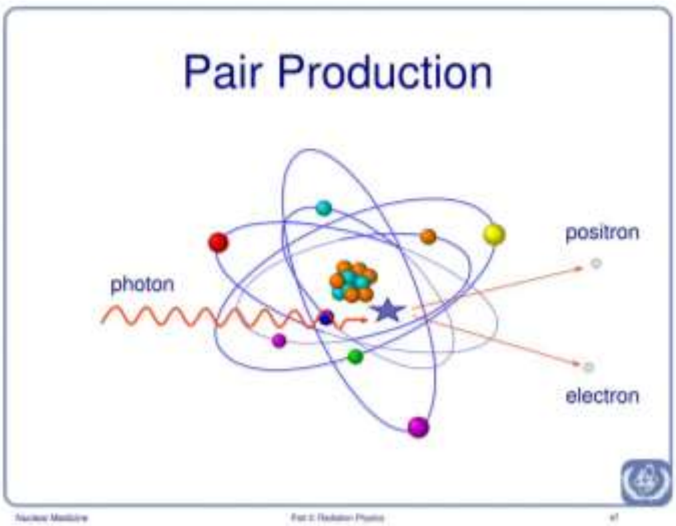


Fig. 9. Schematic of the electron–positron pair production

1.3.4. Rayleigh scattering

Rayleigh scattering consists of the coherent scattering of light without a change in wavelength, does not contribute to the energy change of photons, and therefore cannot serve as a detection method.

1.4. Monte-Carlo method.

The Monte Carlo method is a set of numerical methods that are used to study random processes. It involves creating a mathematical model of the process and using a random number generator to repeatedly simulate the process. From the data obtained, the probability characteristics of the process are calculated. The Monte Carlo method is used in various fields such as physics, chemistry, mathematics, economics, optimization, control theory and others.

The algorithm of the method consists of the following basic steps:

1. Generate **N** random "points" $\boldsymbol{x_i}$ in the problem space
2. Calculate the "score" $\boldsymbol{f_i = f(x_i)}$ for the **N** "points"
3. Calculate $\boldsymbol{< f >= \frac{1}{N}\sum_{i=1}^{N} f_i}$, and $\boldsymbol{< f^2 >= \frac{1}{N}\sum_{i=1}^{N} f_i^2}$
4. According to the Central Limit Theorem, for large range **N** $\boldsymbol{< f >}$ will approach the true value $\boldsymbol{f}$. More precisely:

$$\boldsymbol{p(< f >) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[\frac{-(< f > - f)^2}{2\sigma^2}\right]}$$

$$\boldsymbol{\sigma^2 = \frac{< f^2 > - < f >^2}{N - 1}}$$

This method is often used in science because of a number of advantages:

- The Monte Carlo method can be applied to a wide range of problems in physics, including problems that cannot be solved analytically.
- If the Monte Carlo method is used correctly, high accuracy of the results can be achieved.
- The Monte Carlo method is relatively simple to implement and can be easily automated.

1.5. MCNPX for modeling radiation transport in matter.

Monte Carlo N-Particle eXtended (MCNPX) is a general-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo radiation transport code designed to track many particle types over broad ranges of energies. It is capable of simulating particle interactions of 34 different types of particles (nucleons and ions) and 2000+ heavy ions at nearly all energies [13].

The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori.

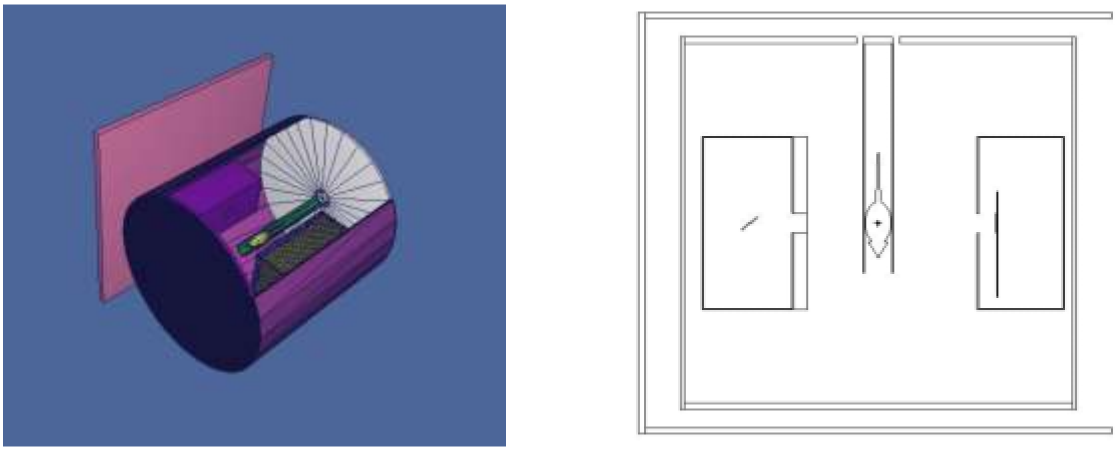
For photons, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung. A continuous-slowing-down model is used for electron transport that includes positrons, k x-rays, and bremsstrahlung but does not include external or self-induced fields.

MCNPX is very versatile and easy to use. Includes a powerful general source, criticality source, and surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data. The key value MCNPX provides is a predictive capability that can replace expensive or impossible-to-perform experiments.

2. Results

2.1. CT

To plot the dose rate-distance dependence of the preclinical SPECT/CT scanner, modeling sessions were performed using the MCNP code. The geometry of the model is shown in Figure 10. The origin of the coordinates was chosen to be the center of the phantom mouse heart. A protective wall of lead was placed at a distance of 33 centimeters along the x-axis, with its thickness varying from zero to two centimeters.



(a) (b)

Fig. 10. The geometry of SPECT/CT scanner. (a) - 3D view, (b) - overhead 2D view.

X-ray tube with a tungsten anode was modeled as a point source placed in front of the anode emitting in the direction of the target with a solid angle of 20 degrees, having the x-axis itself as its axis. The number of photons from the X-ray source was chosen to be one million.

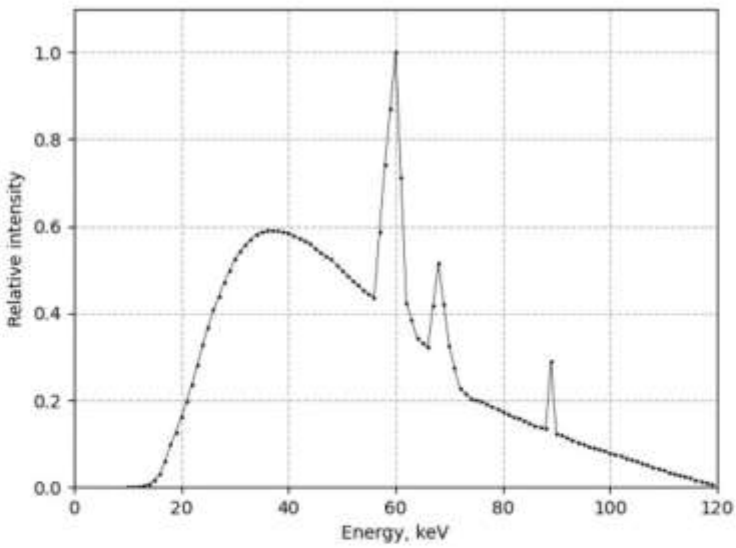
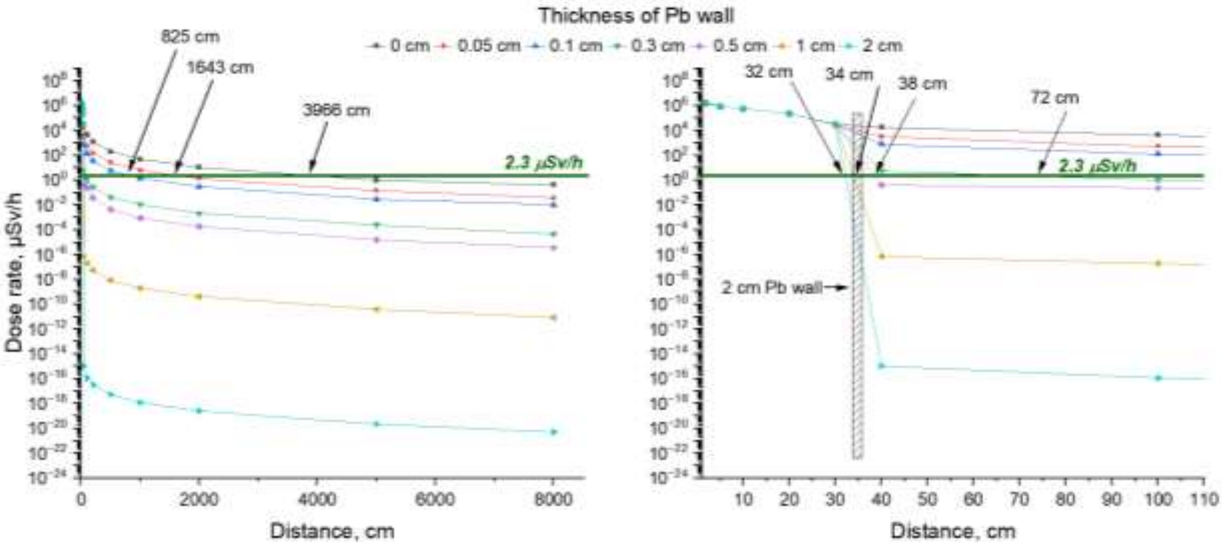


Fig. 11. X-ray tube spectrum with tungsten cathode.

The results for the computed tomography simulation are shown in Figure 12.



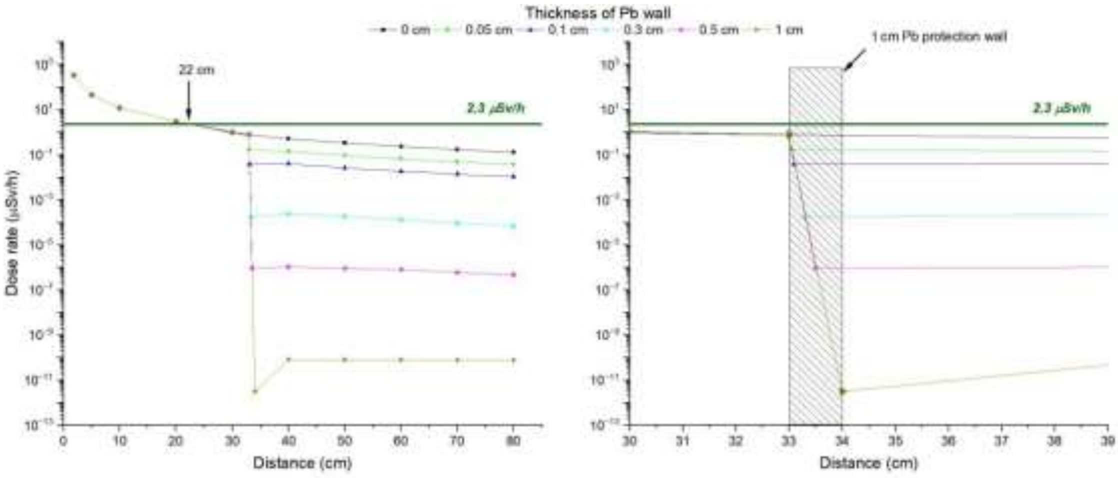
(a) (b)

Fig. 12. Dependency of dose rate vs distance from X-ray source in CT setup: (a) - full view, (b) - expanded view of the low distances region.

The intersection points demonstrate the safety distance in cm for different lead wall thicknesses. In the graph, these points are marked with arrows for convenience. The shaded rectangle shows the area in which the thickness of the lead shielding varied. The graph shows that, in the absence of protection, it is not safe to be at a distance undo 3966 centimeters from the radiation source, i.e. at a distance of about 40 meters. In such a case a lead shield of at least 1 cm must be used for the safety of the worker.

2.2. SPECT

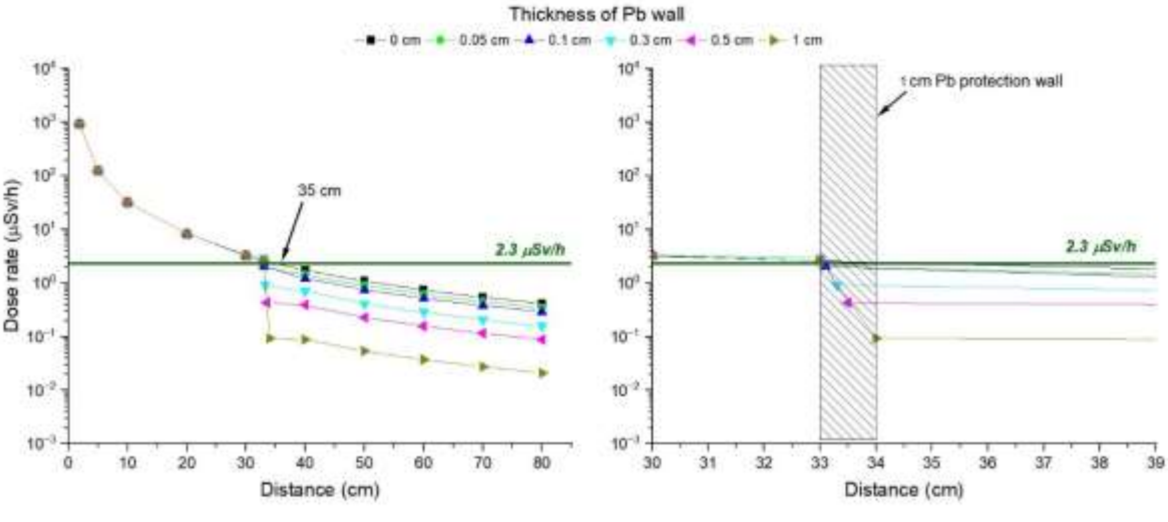
In the case of SPECT scans, the radiation source $^{99m}\mathrm{Tc}$ was placed at the origin (0, 0, 0). In addition, the radiation direction was isotropic, i.e., into the range of 4π angles with an energy of 140 keV. The number of photons was also equal to one million. However, in this case, the lead protection varied from zero to one cm. The results of the simulation are presented in Figure 13.



(a) (b)

Fig. 13. Dose rate dependence on distance to ^{99m}Tc gamma source in SPECT setup: (a) - full view, (b) - expanded view of the low distances region.

The graphs clearly show that the safe dose from the ^{99m}Tc. source is reached at a distance of 22 centimeters, i.e., before the lead shielding, exactly inside the gantry, where the personnel operating the scanner does not have access when it is in use. This means that the presence of lead shielding is not required to protect the working person in this case.



(a) (b)

Fig. 14. Dose rate dependence on distance to ^{131}I gamma source in SPECT setup: (a) - full view, (b) - expanded view of the low sdistances region.

In this case we see that when no lead wall is used, the safe distance is 35 cm. In this case, it is obviously better to use a minimum lead thickness of half a millimeter guarantees safety for personnel.

Conclusions

The discovery of radioactive elements and their use in medicine triggered the development of new ways to study people. One of the most popular research methods to this day is hybrid CT/SPECT scanning. Such a combination of two methods allows to fully collect data on the state of the patient's internal organs, as well as the presence of malignant growths, without resorting to surgery.

However, one of the disadvantages of this method is the danger to the worker who conducts such research every day. This project, which used a MCNP code based on the Monte Carlo method, allowed us to estimate the degree of protection required for a health care worker.

Simulations have shown that lead shielding is effective in reducing radiation exposure to occupationally exposed personnel. The results of the study can be used to optimize the design of lead shielding, such as determining the optimum thickness and arrangement of shielding layers to minimize radiation exposure to personnel while maintaining the convenience and efficiency of the CT and SPECT procedure.

For example, the results showed that it was unsafe for a worker to use an X-ray tomography with a tungsten anode without lead shielding. In this case, a minimum of 1 centimeter of lead shielding is required.

In the case of SPECT scans, the results differed for different radionuclides. For example, the use of $^{99m}\mathrm{Tc}$ with a photon energy of 140 keV does not require protection of personnel from radiation, since the safe distance is exactly inside the gantry, where the personnel who operate the scanner do not have access when it is in use. However, when $^{131}\mathrm{I}$ with photon energy 364 keV is used, a thin 0.5 mm layer of lead would be sufficient for complete safety.

Many processes of interaction of particles with matter, especially at microscopic scales, are stochastic. The Monte Carlo method allows modelling these processes, taking into account random trajectories and probabilistic characteristics of particle interactions. In addition, this method allows to simulate the interaction of particles with matter in complex geometric configurations, such as volumetric objects, surfaces, etc. This is especially important for applications in medicine, nuclear energy, astrophysics and other fields.

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Acknowledgments

I would like to thank my supervisor Dr Antonio Leyva Fabelo for his time and patience while working on this project. In addition, many thanks to JINR University Centre for the opportunity to explore new areas of science and the availability of a wide range of project topics.