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”

Student:
Deniel Rodriguez, Cuba
InSTEC, Havana University

Supervisor:
Dr. Antonio Leyva Fabelo

Consultant:
Lic. Elizabeth Vega Moreno

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Abstract

The safety of individuals exposed to ionizing radiation in medical settings, where advanced diagnostic and treatment technologies like X-rays, CT scans, PET, and SPECT are used, is crucial. Mathematical modeling of radiation transport is essential to ascertain the safest operational conditions and simulate dose distribution accurately and cost-effectively. A study focused on utilizing mathematical simulations to analyze dose rate distribution near preclinical SPECT and CT systems aimed to determine the minimum safe distance based on international standards and find the optimal lead wall thickness to minimize radiation exposure. The Monte Carlo N-Particle (MCNPX) code system was employed, showing that a lead wall thickness of 0.5 cm is optimal for the CT case to keep the dose rate below 2.3 μSv/h and ensure safety. For the SPECT case, the required lead wall thickness depends on the specific radioisotope used, with technetium-99m and thallium-201 requiring no lead wall due to their low dose rates, while iodine-131 necessitates a 0.05 cm lead wall to maintain the dose rate below the permissible level.

Introduction

The safety of all personnel and visitors in environments where ionizing radiation is used, especially in diagnostic and medical treatment techniques such as X-rays, gamma cameras, computed tomography (CT), PET, and SPECT, is of vital importance. To determine the safest and most efficient conditions for the operation of these systems, mathematical modeling of radiation transport plays an essential role. This approach allows for precise simulations of dose distribution and other critical parameters, quickly and cost-effectively. In this study, utilizing mathematical simulations, the dose rate distribution was analyzed in different configurations and sources near preclinical SPECT and CT equipment. The aim is to estimate the minimum safe distance for health based on international standards and determine the optimal thickness of the protective lead wall to minimize radiation exposure.

Materials and Methods.

SPECT/CT tomography.

CT

A CT scanner, also known as a computed tomography (CT) machine, employs X-rays to create cross-sectional images (slices) of the body. These images are generated by rotating the X-ray tube around the patient while they lie on a table, providing a detailed view of tissues, organs, and internal structures. Notably, the CT scanner can rapidly acquire images, which is crucial in emergency situations. It also offers high spatial resolution, enabling the detection of subtle anomalies, such as minor differences in tissue density. This capability is especially useful for visualizing organs, tumors, fractures, and other abnormalities. The scanning process is swift and typically completes within minutes, making it essential for emergencies or urgent assessments. The CT scanner can be used to explore various body parts, including the brain, chest, abdomen, and bones.

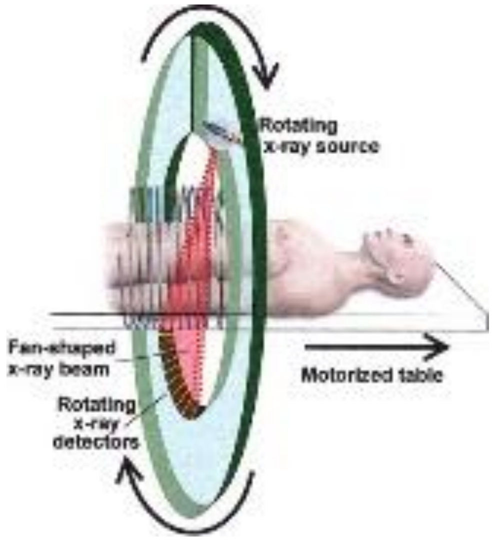

Fig. 1. *Main components of the CT and lateral view of the helical trajectory (Zona Radiology. (2013, Octubre). Perkembangan CT Scan Generasi I hingga Sekarang. Recuperado de: http://zonaradiology.blogspot.com/2013/10/perkembangan-ct-scan-generasi-i-sekarang.html)*

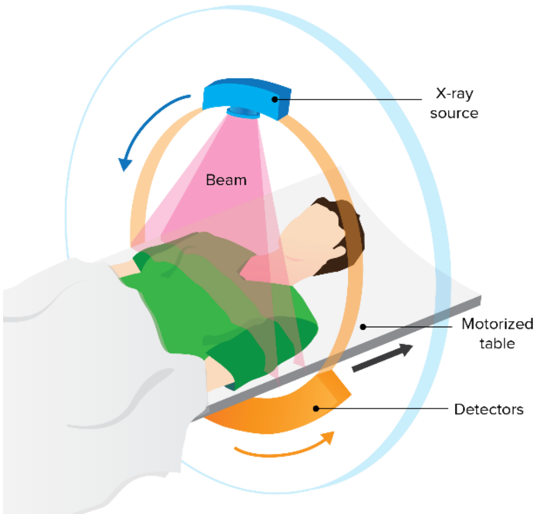

Fig. 2*. Semi-frontal view of operation of the x-ray source and detectors (Lecturio. (s.f.). Computed Tomography (CT). Recuperado de: https://www.lecturio.com/concepts/computed-tomography-ct/)*

The advantage of using this scanner lies in obtaining more detailed images than conventional X-rays, all within a few minutes and with high efficiency. Specifically, it excels in revealing bone anatomy and aids in identifying diseases, injuries, and medical conditions. Additionally, it plays a crucial role in surgical planning and treatment decisions.

However, there are drawbacks to CT scanner usage. It involves a small but significant exposure to ionizing radiation, which is not recommended during pregnancy and may cause nausea and dizziness in some patients.

SPECT

The Single Photon Emission Computed Tomography (SPECT) scanner is a medical imaging technique that utilizes a radioactive tracer to generate three-dimensional images. Unlike a simple anatomical image, SPECT monitors the level of biological activity at each point within the analyzed 3D region. The emissions from the radionuclide indicate the amount of blood flow in the capillaries of the imaged regions.

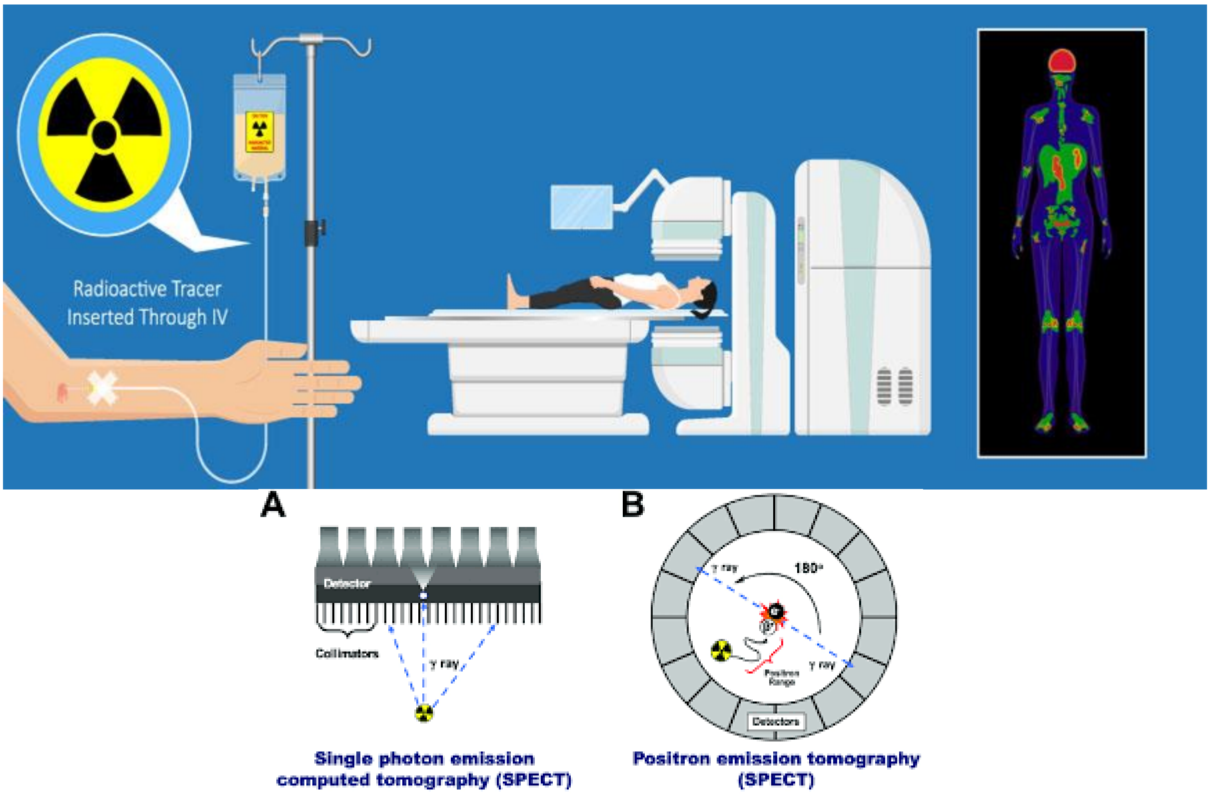

***Fig. 3**. Representation of the operation of a SPECT scanner (Health Library - Apollo Hospitals. (s.f.). What is a SPECT Scan Commonly Used For? Recuperado de: https://healthlibrary.askapollo.com/what-is-a-spect-scan-commonly-used-for/)*

SPECT employs gamma rays produced by radioactive isotopes, such as technetium-99m (where the isotope directly produces the gamma ray), which are introduced into the human body as part of biologically active molecules. During a SPECT scan, the gamma-ray camera rotates around the patient, acquiring images at defined angles (typically every 3-6 degrees). In most cases, a full 360-degree rotation is performed to obtain optimal three-dimensional reconstruction. Each image typically takes 15 to 20 seconds, and the entire process lasts 15 to 20 minutes. Multiple-headed gamma cameras can also be used to expedite the process.

Unlike standard anatomical images, SPECT provides functional information, revealing the functioning of organs and tissues, not just their structure. For instance, it can unveil cerebral activity in specific areas or assess blood flow to the heart, identifying any abnormalities. SPECT is also used to evaluate cardiac issues by highlighting problematic areas, aiding in the detection of obstructed coronary arteries.

Despite being an excellent detection mechanism, Single Photon Emission Computed Tomography (SPECT) has some disadvantages:

1. Lower Spatial Resolution: While SPECT provides excellent visualization of tissue and organ function and structure, its spatial resolution is inferior to other imaging techniques such as computed tomography (CT) or magnetic resonance imaging (MRI). This means that SPECT may not be as precise in detecting small anomalies or fine anatomical details.
2. Radiation Exposure: Like other nuclear medicine tests, SPECT uses a small amount of radiation. Although it is not associated with long-term health risks, it is essential to consider radiation exposure, especially for patients requiring multiple scans over time.
3. Limited Availability: Compared to Positron Emission Tomography (PET), SPECT is less common and less readily available in many medical centers. This limited availability can hinder access to this technique in certain areas or clinical situations.
4. Short Radioisotope Half-Life: The radioisotopes used in SPECT have a limited lifespan. Careful planning is necessary to ensure that patients are prepared for the examination at the right moment.

As radiation sources in SPECT, besides technetium-99m, other isotopes such as thallium-201 for cardiac studies or iodine-123 for brain imaging are also utilized. The choice of isotope depends on the clinical objective and availability.

SPECT-CT

SPECT/CT technology represents an advanced modality in medical imaging that combines information from two distinct technologies: Single Photon Emission Computed Tomography (SPECT) and Computed Tomography (CT). It utilizes radiopharmaceuticals to obtain functional images of the body. This technology provides detailed anatomical images by merging the functional SPECT images with the anatomical CT images. As a result, it enables precise correlation between metabolic function (SPECT) and anatomy (CT), offering more accurate information about complex or diagnostically challenging organ and anatomical structures.

This mechanism finds significant utility in the following sectors:

1. Cardiology: It evaluates blood perfusion in the heart and detects areas with inadequate blood flow.
2. Oncology: SPECT/CT assists in locating tumors, assessing their extent, and planning treatments.
3. Neurology: It allows the study of brain diseases, including epilepsy, dementia, and vascular disorders.

***Fig. 4**. Semi-frontal view of a latest generation Siemens SPECT-CT (Siemens Healthineers. (s.f.). SPECT/CT Scanner. Recuperado de: https://www.siemens-healthineers.com/molecular-imaging/spect-ct-scanner)*

One advantage of using this technology is its ability to pinpoint anomalous areas with greater precision. Additionally, it evaluates treatment response from early stages and reduces radiation exposure. By combining both techniques, the need for separate studies is minimized.

Dose safe limits.

The Annual Effective Dose for Patients is considered to be within a safe range of approximately 1-20 mSv per year. This range varies depending on the type of radiological study and the age of the patient. Typical effective doses for different imaging procedures vary; For example, a plain chest x-ray may involve a dose of 0.1-0.2 mSv, while an abdominal CT scan is around 10 mSv. During interventional procedures such as fluoroscopy, where more intense real-time radiation is used, dose limits vary but are generally rigorously controlled to ensure the safety of both patients and medical staff. In general, the permitted dose rate is 20 mSv/year or 2.3 μSv/h.

Interaction of photons with matter.

Interaction of Photons with Matter: Photons, being chargeless and massless particles, primarily interact with matter through three processes:

1. Photoelectric Effect: A photon collides with an electron in an atom, transferring all its energy and causing the electron's release. This process is fundamental in radiological image formation.
2. Compton Effect: The photon collides with an electron, transferring part of its energy. The photon deviates and changes its wavelength. This process is significant in radiation scattering.

3. Pair Production: In the presence of a strong electric field (such as near an atomic nucleus), a photon can convert into an electron and a positron (the electron's antiparticle). This is crucial in particle production within particle accelerators.

Interaction of Charged Particles with Matter: Charged particles (such as electrons or protons) also interact with matter in various ways:

1. Elastic and Inelastic Collisions: Charged particles can collide with atoms in the medium, deflecting and transferring kinetic energy. These collisions can be elastic (without atomic alteration) or inelastic (resulting in ionization or excitation).
2. Stopping Power and Range: Charged particles lose energy while traversing matter. Stopping power and range depend on the particle's energy and the medium.
3. Interaction of Heavy Particles: Heavier charged particles can also interact with medium atoms, producing ionization, excitation, and radiation braking.

Interaction of Neutrons with Matter: Neutrons also interact with matter through elastic and inelastic collisions, as well as neutron capture processes and neutron-induced fission reactions.

Montecarlo method.

The Monte Carlo method is a simulation technique used to solve complex problems by generating pseudo-random numbers to simulate random events. These numbers are generated from deterministic algorithms and are uniformly distributed within a predefined range. In this method, a domain of possible inputs is defined, and random values are generated for each parameter. The results are aggregated and averaged to obtain an estimation of the final outcome. The Monte Carlo method finds extensive application in physics, mathematics, finance, engineering, statistics, and other disciplines because it allows solving complex problems that lack a direct analytical solution. Additionally, this method assesses uncertainty by simulating multiple scenarios and providing a distribution of results, enabling the evaluation of uncertainty and estimation of confidence intervals.

MCNPX for modeling radiation transport in matter.

MCNPX

MCNPX (Monte Carlo N-Particle eXtended) is a simulation program used to study the interaction of different particles with matter. Through the Monte Carlo method, MCNPX simulates all interactions and secondary particles originating from these interactions.

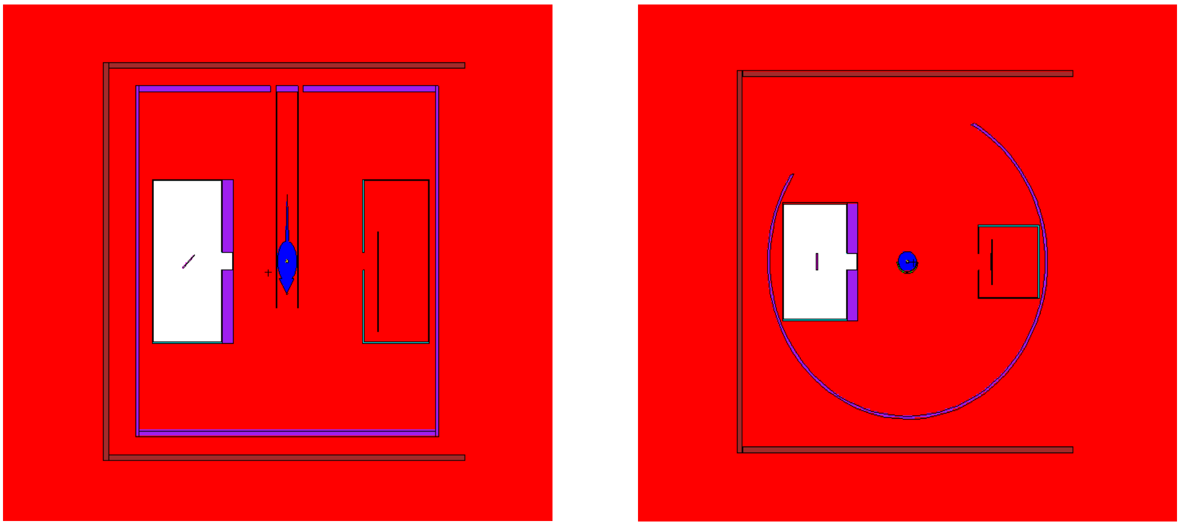

Fig. 5. *2D view of SPECT/CT without lead wall*

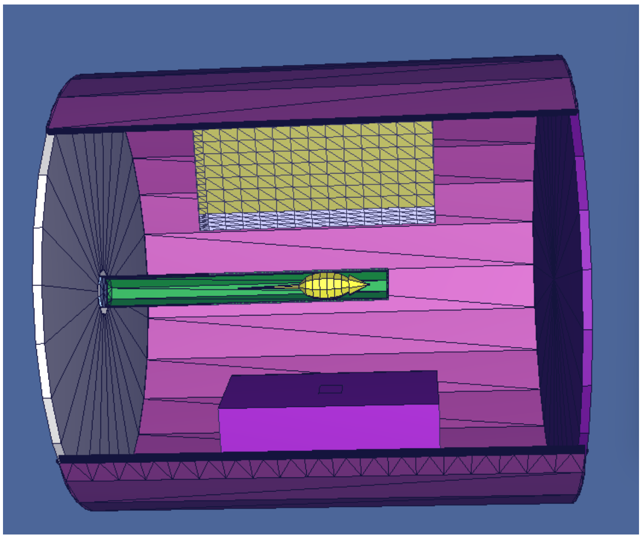

Fig. 6. *3D view of SPECT/CT without lead wall*

MCNPX is employed to model and simulate complex three-dimensional geometries in radiation therapy and other medical fields. It is used for radiation protection, shielding, and safety evaluation by estimating energy deposited per unit mass. Additionally, MCNPX simulates particle transport in nuclear reactors. The program can also model particle interactions in accelerators and other particle physics experiments.

Key features of the MCNPX code include:

1. Monte Carlo Method: MCNPX accurately models particle interactions with matter using the Monte Carlo method.
2. Detailed 3D Geometries: It describes intricate three-dimensional geometries in great detail, which is crucial for applications like medical dosimetry and nuclear reactor design.
3. Material Modeling: MCNPX includes an extensive library of materials with specific properties, allowing precise simulation of various substances and compounds.
4. Secondary Particle Tracking: The code tracks all secondary particles generated by initial interactions, providing comprehensive information about resulting radiation.
5. Particle Sources: Various particle sources, such as neutron beams, gamma rays, or alpha particles, can be defined.

MCNPX plays a vital role in predictive capabilities, replacing expensive or impractical experiments and saving time and costs for the scientific community.

In this field, SPECT/CT technology is also utilized in Radiation Therapy Treatment Planning. It can simulate dose distribution in tissues and organs during radiation therapy. Additionally, it calculates the dose delivered to the tumor and surrounding tissues, which is crucial for designing personalized treatments and minimizing side effects while optimizing treatment planning. MCNPX can simulate photon and electron beams used in radiation therapy. It is employed to design shielding in medical facilities, such as radiation therapy treatment rooms or nuclear medicine laboratories. Furthermore, it evaluates the effectiveness of shielding materials and radiation exposure in the clinical environment. MCNPX is used to simulate dose detectors and verify the accuracy of in vivo measurements during radiation therapy treatments, ensuring that the administered dose aligns with the planned dose. Moreover, MCNPX enables exploration of novel treatment techniques, such as proton therapy or heavy ion beam therapy, facilitating research on particle interactions with different tissue types. It is also utilized to study the radiation dose received by patients during imaging procedures, such as computed tomography (CT) scans or gammagraphies, contributing to the establishment of safe and efficient imaging protocols.

Origin

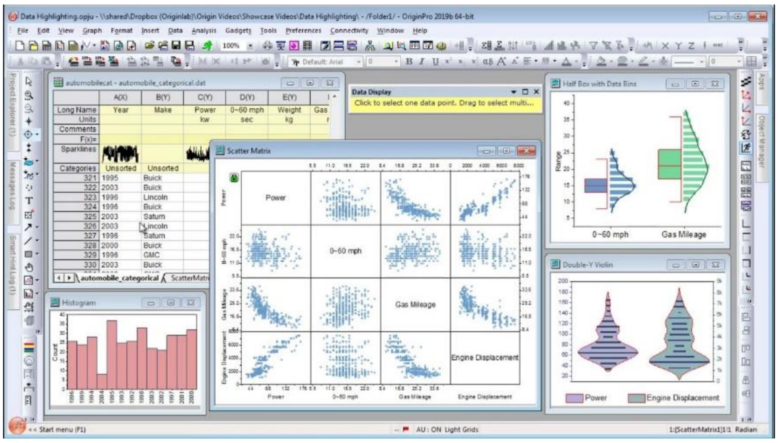

***Fig. 7**. Origin data analyzer representation (OriginLab Corporation. (s.f.). Origin. Recuperado de: https://www.originlab.com/Origin)*

Origin, widely used scientific software, serves as a powerful tool for data analysis and graph creation. It provides a beginner-friendly interface while allowing advanced customization as users become more familiar with the application. Origin enables data import and manipulation from various sources, calculations, filtering, and data transformation to suit specific needs. With over 100 built-in and customizable graph types, you can create both 2D and 3D graphs, adjust axes, panels, labels, and plot styles. Notably, Origin includes tools for curve fitting, surface analysis, peak analysis, descriptive statistics, and parametric/non-parametric tests. Additionally, it offers features for data exploration and relevant information extraction. Origin allows users to create templates for repetitive tasks or perform batch operations without programming. It seamlessly integrates with other applications like MATLAB™, LabVIEW™, or Microsoft© Excel, and supports custom routines using languages such as C, Python, or R. Beyond Origin's capabilities, OriginPro provides advanced tools for data analysis, peak fitting, statistics, and signal processing.

Results.

SPECT

In Figure 8, we can observe the dose rate as a function of distance for technetium-99m, where we notice that the distance at which the dose rate no longer exceeds the permissible dose rate is 22.62 cm from the source. This point is located within the gantry, before reaching the distance where the lead wall would be situated (approximately 32 cm). We can conclude that there is no need to install a lead wall for this equipment.

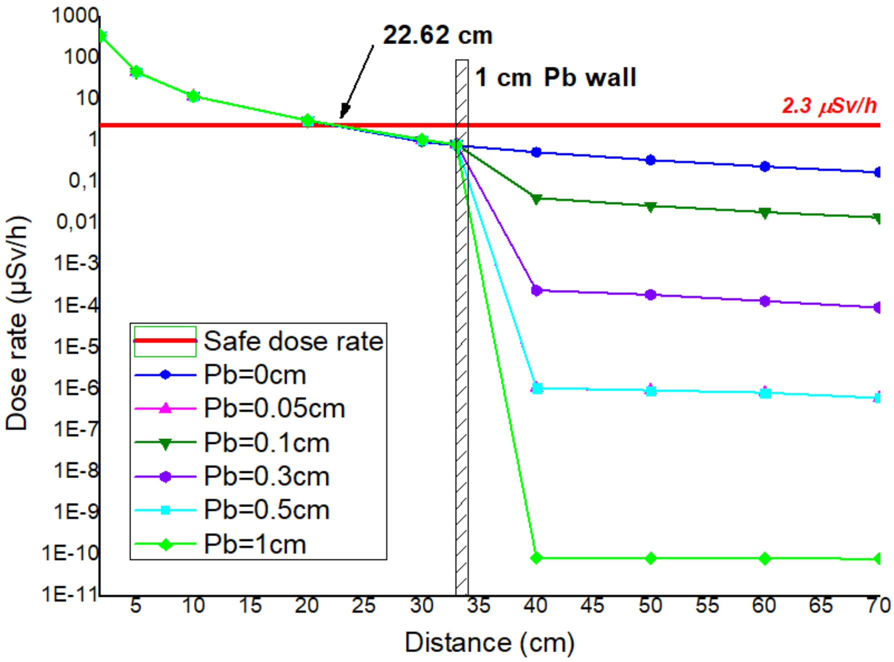

Fig. 8. *Dose rate as a function of distance for Tc-99m*

In Figure 9, we can observe the dose rate as a function of distance for iodine-131. It is evident that the dose rate exceeds the permissible value only when there is no lead wall. This occurs at a distance of 35.43 cm from the source. Since this point lies beyond where the lead wall would be positioned, it is necessary to install one. A 0.05 cm thick lead wall is sufficient to ensure that the dose rate remains below the permissible limit, making the area safe for personnel.

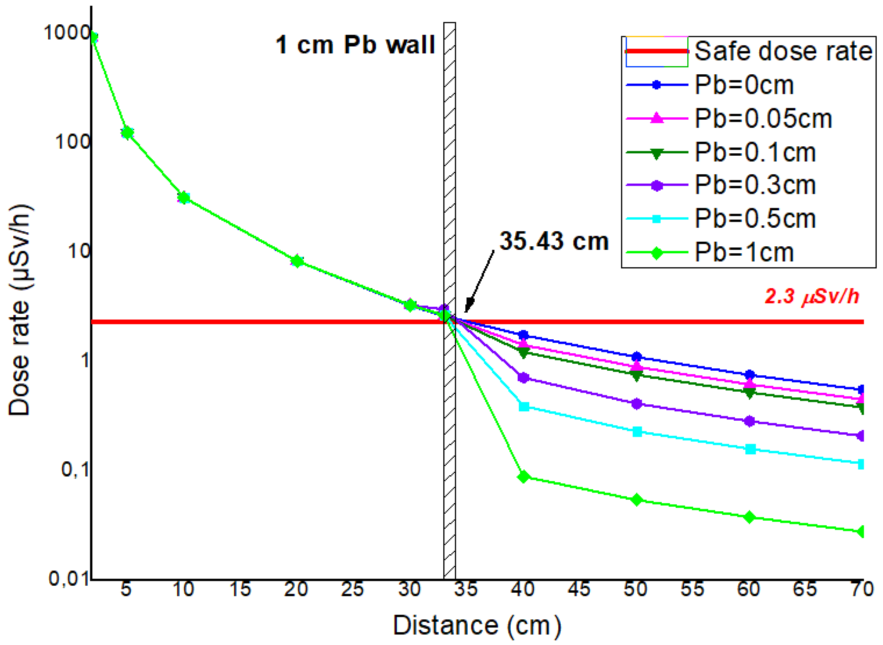

Fig. 9*. Dose rate as a function of distance for I-131*

In Figure 10, the dose rate is observed as a function of distance for thallium-201. At a distance of 17.27 cm from the source, the dose rate no longer exceeds the permissible level. Since this point is located inside the scanner gantry, before the distance where the lead wall is placed, then it is not necessary to install said wall.

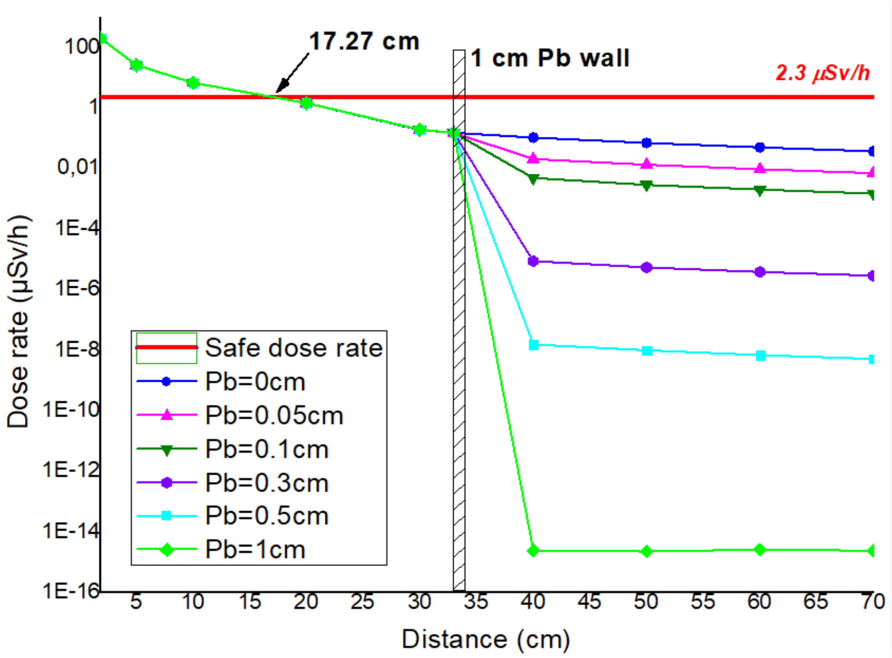

Fig. 10. *Dose rate as a function of distance for Tl-201*

CT

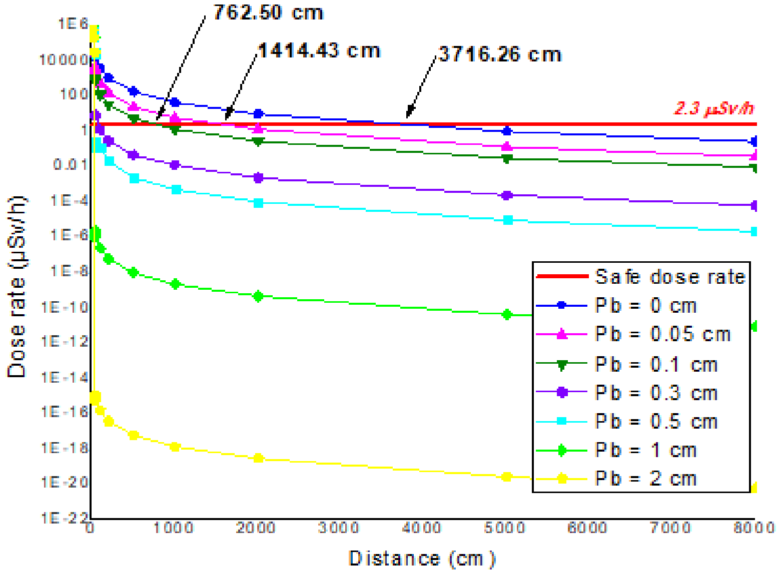

***Fig. 11**. Dose rate as a function of distance for CT*

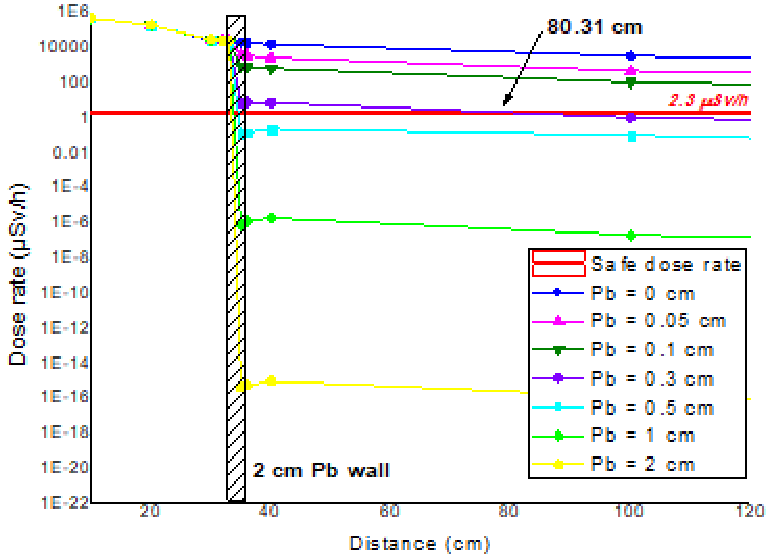

***Fig. 12**. Dose rate as a function of distance for CT (ZOOM).*

In Figure 11, we can observe that the distance at which the dose rate level due to radiation emitted by the CT is safe, assuming no protective wall exists, is 3716.26 cm from the emission source. However, this distance is not efficient for a facility where this service is performed. The same holds when using a lead wall with thicknesses of 0.05 cm and 0.1 cm, for which the safe distances are 1414.43 cm and 762.50 cm, respectively.

Expanding the X scale in on Figure 11 (now referred to as Figure 12), we find that for a lead wall thickness of 0.3 cm, the distance at which the dose rate level exceeds the established limit is 80.31 cm beyond the source, approximately 48.31 cm beyond the wall. For a lead wall thickness of 0.5 cm or greater, the dose rate level remains below the permissible limit, as shown in the figures, at 2.3 μSv/h.

Conclusions.

Using the Monte Carlo N-Particle (MCNPX) code system, which is based on the Monte Carlo method, it was possible to simulate the dose rate distribution in a preclinical SPECT-CT image scanner. For a detailed study of the task, a tungsten X-ray tube was employed for the CT case, along with three different gamma radioisotopes for the SPECT case. Additionally, the thickness of a lead wall was varied within the range of 0 cm to 2 cm. The dose rate for each geometric arrangement was measured at different distances from the source in both cases and compared with the internationally recognized safe dose of 2.3 μSv/h.

Therefore, we conclude that for the CT case, the optimal lead wall thickness at which the dose rate does not exceed the permissible value of 2.3 μSv/h is 0.5 cm. With this thickness, we ensure that the facility remains safe for all personnel.

Regarding the SPECT case, the lead wall thickness required to ensure that the dose rate does not surpass the permissible level will significantly depend on the specific radioisotope source being used. In our scenario, we employed technetium-99m, iodine-131, and thallium-201. For these isotopes, the dose rate is very low due to their energy and activity.

Interestingly, for technetium-99m and thallium-201, there is no need to install the lead wall because the dose rate ceases to exceed the permissible level at a distance prior to where the wall would be placed, essentially, within the equipment gantry. However, in the case of iodine-131, the optimal lead wall thickness beyond which the dose rate remains below 2.3 μSv/h is 0.05 cm.

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