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 a preclinical SPECT/CT scanner"

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Abstract

SPECT-CT is a hybrid imaging technique popular at the current time because it combines the advantage of SPECT in metabolism and physical processes with the high resolution of CT. Even so, both methods involve radiation causing the determination of shielding to be a priority for occupationally exposed workers, the ones more affected. The ICRP establishes the dose rate limit for occupationally exposed workers at 2.3 µSv/h. MCNP code is efficient in radiation transport in matter becoming a valuable tool for dose rate estimation, avoiding the radiation risk of the experimental measurement. The hybrid system was simulated and safe distance was estimated after plotting the dose rate vs the distance for different lead wall thickness. For ^{99m}Tc, ^{123}I, ^{133}Xe used in radiopharmaceuticals in SPECT analysis the safe distance was less than 30 cm and inside the gantry making the lead wall unnecessary for the three isotopes. For CT simulation a gamma source from an X-ray tube with a tungsten anode, the safe distance for no wall was calculated and the result obtained was 3600 cm. Was determined that the optimal wall thickness was 0.75 cm turning the safe distance to 33.5 cm (inside the lead wall) and the maximum amount of dose rate received was estimated for the operator after the wall 3.6E-2 µSv/h, 1.5 percent of the dose rate limit.

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Introduction

Radiological protection is a critical field focused on ensuring the safe use of radiation in medical, industrial, and research settings. It involves principles and practices designed to minimize radiation exposure to patients, workers, and the public while maximizing the benefits of radiation-based technologies. In medicine, advanced imaging techniques such as SPECT-CT (Single Photon Emission Computed Tomography combined with Computed Tomography) have revolutionized diagnostics by providing detailed functional and anatomical information. These hybrid imaging modalities allow for precise localization of diseases, particularly in oncology, cardiology, and neurology.

To optimize these technologies and ensure safety, computational tools like Monte Carlo simulations play a vital role. Monte Carlo methods are used to model the transport of radiation through matter, providing insights into dose distribution, imaging quality, and the development of new medical applications. Together, radiological protection, advanced imaging techniques, and Monte Carlo simulations form the backbone of modern radiation medicine, enabling safer and more effective healthcare solutions.

The main goal of this paper is:

- Study radiation shielding determination in a preclinical SPECT-CT system with MCNP code.

The specific plan to follow for this goal is:

1. Modeling a preclinical SPECT-CT system.
2. Obtain 2D and 3D images from scanner vised61_24j.59.
3. Obtain photon and secondary electrons tracks with the gamma and the X-ray source.
4. Determination of the shielding thickness for SPECT and CT components.

Materials and Methods.

Interaction of photons with matter.

Photons, such as X-rays and gamma rays (Herbert Attix, 2004), are particles with no mass or electric charge and can interact with matter through several mechanisms. These interactions depend on the energy of the photon and the properties of the material with which it interacts. The most common methods are the Photoelectric Effect, Compton Scattering, Pair Production, Auger Effect, and Rayleigh Scattering (Eisberg, 1985).

Photoelectric Effect.

In the Photoelectric Effect (PE) the photon ($h\upsilon$) is completely absorbed by one of the internal electrons of the atom, providing the electron with enough energy (E') to escape from its stationary orbit and ionize the material; this energy depends of the ionization potential (B_k) characteristic of material and atom-shell (figure 1 left) This effect is most commonly produced for energies below 100 keV and material

with high atomic number (B Nilsson, 2014). The PE is mostly significant in the formation of CT images.

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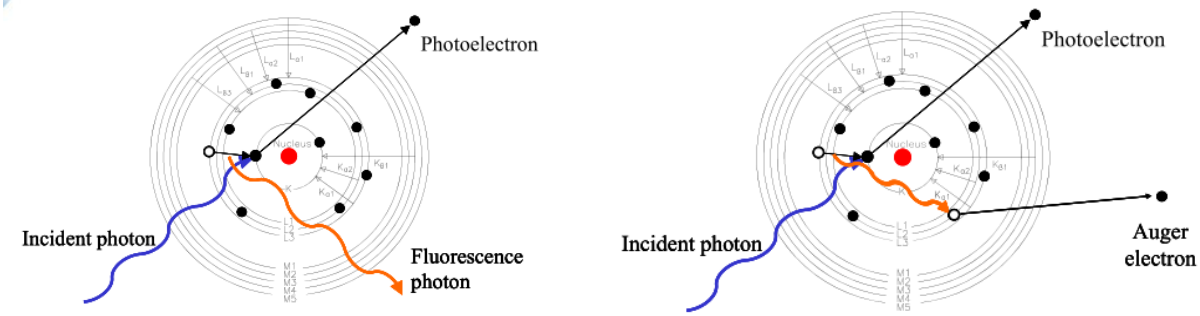


Fig.1: Photoelectric (left) and Auger (right) Effect Schematic (Pepponi, 2015).

After the production of the PE, the vacancy created by the escaped electron can be filled by an electron from a higher energy level; the excess of energy from the descending electron is emitted as a photon with a characteristic energy describing the transition between the two energy levels, this photon is known as X-ray. If this photon is absorbed by another electron from a higher orbit causing the emission of the electron of his shell, this electron is called a secondary electrons and the phenomenon Auger Effect (figure 1 right).

Incoherent (Compton) and Coherent (Rayleigh) Scattering.

The Compton scattering is produced when an incoming photon (hυ) interacts with an atomic electron, often a weak bounded or free electron which is emitted with energy E', and the photon is scattered with lower energy (hυ') (figure 2) (B Nilsson, 2014); producing the ionization of the material. This phenomenon is predominant in materials with low atomic number and medium energy (100 keV - 10 MeV).

Also, the photon can be scattered without ionizing the atom, the process is similar to Compton scattering but in this case, there is no energy loss of the incoming particle; only a change in direction; this is called coherent (Rayleigh) scattering because is more like an elastic collision.

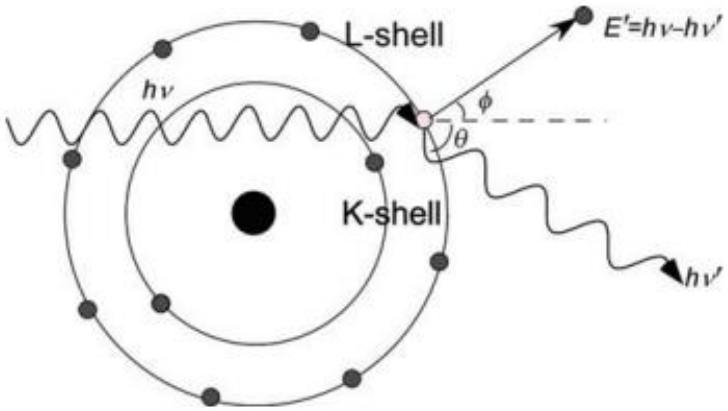


Fig.2: Compton Scattering Schematic.

Pair Production.
When a high-energy photon interacts with the electromagnetic field of the nucleus or electron, a pair of electron-positrons can be emitted as a consequence of the absorption of the photon in the field (figure 3). The minimum amount of energy needed for this effect is 1.022 MeV, two times the electron rest mass.

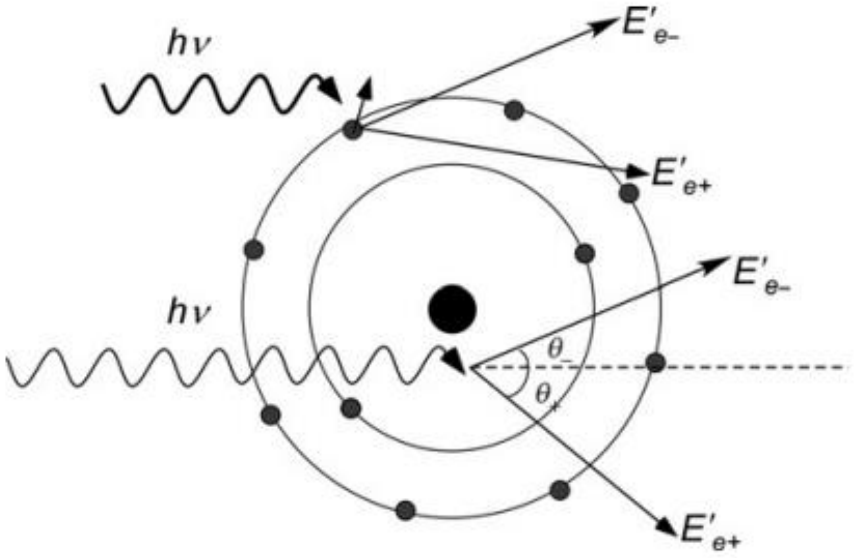


Fig.3: Pair Production Schematic.

<u>Attenuation of photons in matter.</u>

The attenuation of photons in matter is ruled by an exponential law. The simplest way to understand this, is through the linear attenuation law (Ec.1), which establishes a relationship between the intensities of the photon beam before (I_0) and after (I) passing a material of a given thickness (x) with a path perpendicular to the material's surface and its linear attenuation coefficient (μ). The value of the μ coefficient is the sum of the different linear attenuation coefficients related to the mechanism of photon interaction with matter.

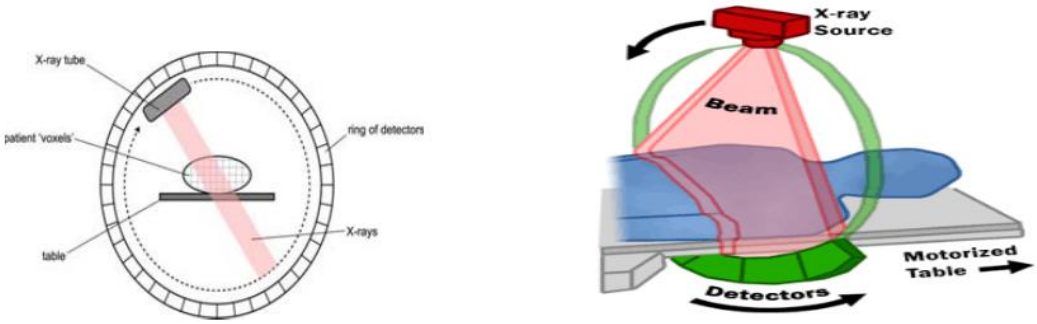
$$I = I_0 * e^{-\mu x}$$

Ec.1: Linear Attenuation Law. (Herbert Attix, 2004)

<u>SPECT/CT tomography.</u>

CT

X-ray CT (Computed Tomography) technology is a medical imaging technique that uses X-rays to create detailed, cross-sectional (slice-like) images of the inside of the body. In CT (figure 4a) an X-ray tube rotates around the patient, emitting a thin beam of X-rays in the shape of a fan (figure 4b) or cone. (Bailey D.L., 2014)



a) CT Scan **b)** CT Fan beam

Fig.4: X-ray CT Imaging (H. Kasban, 2015).

These X-rays pass through the patient's body from different angles. As the X-rays pass through the body, they are attenuated to different degrees depending on the density and composition of the tissues.

On the opposite side of the X-ray tube, detectors measure the intensity of the X-rays after they have passed through the body. These detectors capture thousands of measurements from multiple angles during the rotation of the tube. The measurements from the detectors are sent to a computer, which uses advanced mathematical algorithms to reconstruct a three-dimensional image of the inside of the body. This process converts the attenuation data into a series of cross-sections (or "slices") of the body. The reconstructed images can be displayed on a screen, allowing physicians to examine anatomical structures in detail. The images can be manipulated to view different planes (axial, sagittal, coronal) or even create 3D reconstructions.

The CT is a fast and detailed (high resolution) technique that can be used for almost any part of the body from the brain to the musculoskeletal system and allows the detection of small structures that may not be visible with other imaging modalities.

SPECT

Single Photon Emission Computed Tomography (SPECT) is a nuclear imaging technique in medical physics to creates 3-dimensional images of physiological processes within the body. In this technique, the patient is administrated with a gamma emitter radio-pharmaceutical (molecule biologically designed to accumulate in a certain tissue or organ mark with a radioactive tracer). An array of one to four gamma cameras detects the emitted gamma rays and forms multiple 2-dimensional images by rotating around the patient. These images are reconstructed to form a 3-dimensional representation of the tracer distribution using specially designed software. (Bailey D.L., 2014)

This is a non-invasive technique that provides insights about physiological processes, such as blood flow, and metabolism; with high versatility in various medical fields including cardiology (assessing myocardial perfusion), neurology (detecting brain disorders), and oncology (locating tumors and metastases). SPECT is a quantitative analysis technique for monitoring disease progression and treatment response through the quantification of the tracer uptake.

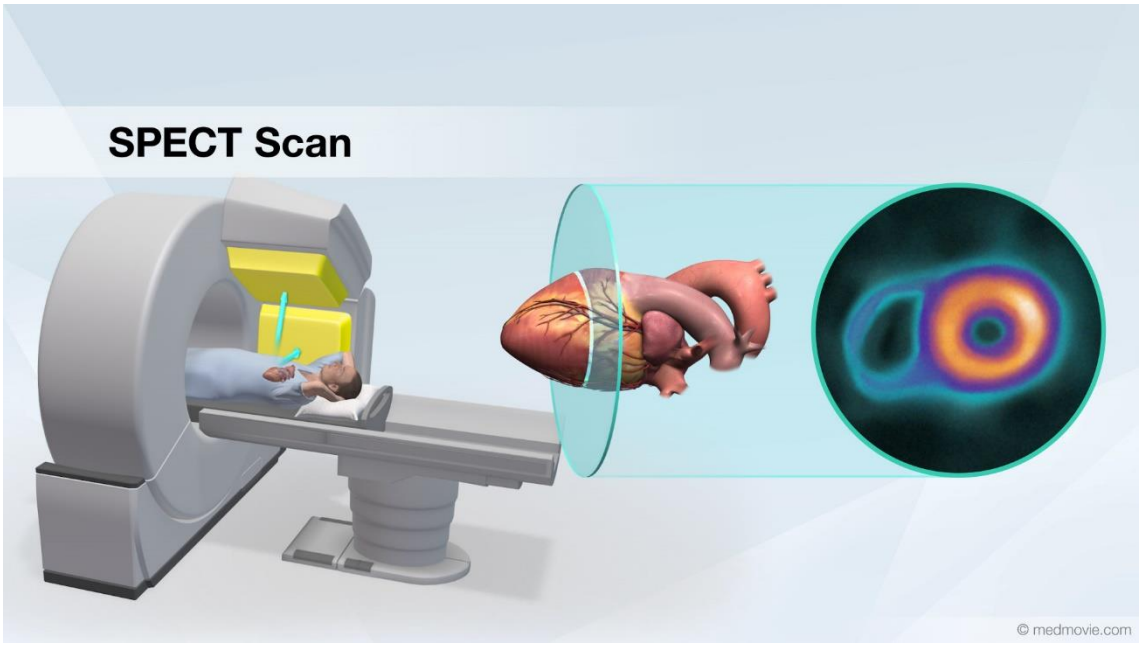


Fig.5: SPECT system (https://th.bing.com/th/id/R.b0cafe5c4c5bad55cfba243efae8f943?rik=7TK%2fcdcNwx9ymw&pid=ImgRaw&r=0).

SPECT-CT

The SPECT-CT (Single Photon Emission Computed Tomography combined with X-ray Computed Tomography) integrates the functional imaging capability of SPECT with the high-resolution anatomical data obtained by CT. In this technique, the patient is administrated with a radiopharmaceutical, and the gamma rays are detected with the gamma camera to create SPECT images. At the same time, a CT scanner is used to obtain anatomical images with X-rays. The two datasets are co-registered, forming a view that combines physiological information with precise anatomical localization. (Bailey D.L., 2014)

The SPECT-CT has greater diagnostic accuracy improving localization and characterization of abnormalities, with respect to SPECT or CT individually, result of its hybrid nature. Allows the acquisition of anatomical and functional data in a single session improving the patient convenience. Also has a reduced radiation exposure with respect to its two components separately; the radiation dose can be reduced by tailoring the CT component to the specific diagnostics needs. Same as SPECT is a quantitative analysis technique, essential to monitoring disease progression and treatment response.

Sources used in SPECT-CT

CT

An X-ray (figure 6) tube is used in CT as a gamma source. The X-ray tube works with a filament and an anode vacuum sealed in an element with an exit window for the characteristic X-rays. When the filament is heated due to the electric current produced from high potential difference, starts emitting electrons

(thermionic emission) that are captured in the anode. The electrons in the anode can produce de-ionization of the material resulting in the emission of the characteristic X-ray. In figure 7 the tungsten (material used for the simulation) anode spectral model distribution is a shower for 1 keV interval.

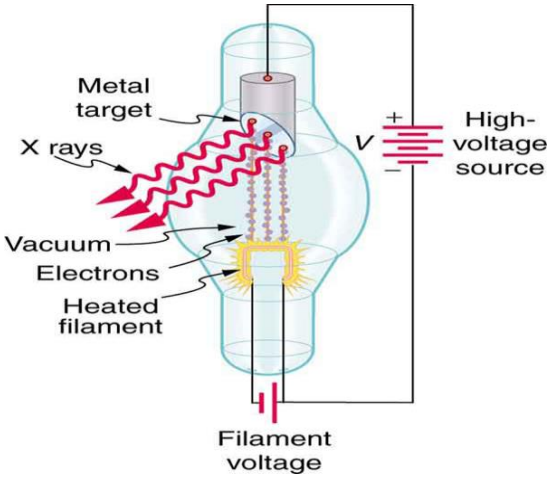


Fig.6: X-ray tube.

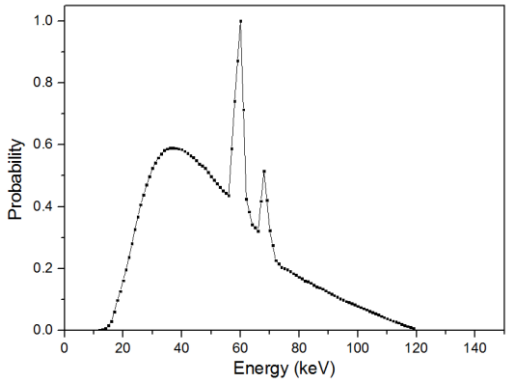


Fig.7: Tungsten Spectral model.

SPECT

For SPECT scan a radio-pharmaceutical is most commonly marked with ^{99m}Tc because of its versatility in different applications (cardiac, bones, brain studies), compatibility with a large number of pharmaceuticals, short half-life, and perfect gamma energy emission for detection (table 1). Other radioisotopes used are ^{123}I employed in thyroid imaging, and dopamine receptors studies, and ^{133}Xe in pulmonary ventilation research.

Table.1: Isotopes employed in SPECT imaging.

Isotope	Energy (keV)	T1/2 (h)
^{99m}Tc	140.5	6.01
^{123}I	159	13.22
^{133}Xe	81	125.76

Dose safe limits.

As good and effective as the SPECT/CT technique for the localization of tumors and research of metabolic processes, in order to create an image, the patient receives a dose of radiation that always produces some cell damage. All cells are capable of recuperation from a certain quantity of radiation damage (Bailey D.L., 2014). The limit dose that a cell is capable of recovering without permanent damage is called the dose safe limit.

Determination of dose-safe limits is in charge of the International Commission of Radiological Protection (ICRP). These values are split into dose-safe limits for the public and for occupationally exposed workers. Is worth mentioning that the dose limits are dependent on the kind of cell that receives the radiation (table 2).

Table.2: Dose Rate Limits (Eckerman K., 2012).

	Dose rate Limit	**Dose limit to the Len of the eye**	**Dose limit to the skin (average per cm^2)**
Occupationally Exposed Worker	2.3 μSv/h	20 mSv per year average in 5 years, with no year > 50 mSv	500 mSv per year
Public	50 μSv/h	15 mSv per year	50 mSv per year

Monte Carlo method.

The Monte Carlo (MC) method is a numerical solution to complex macroscopic systems through the simulation of the microscopic interactions of the system components. The solution is determined by random sampling of the relations of the microscopic component until the result converges. In 1930, Enrico Fermi experimented with this method to study neutron diffusion which was central to the simulations of Project Manhattan (Hendricks John S., 2022).

MCNPX for modeling radiation transport in matter.

Monte Carlo for N-Particle eXtended (MCNPX) was released in 1999 as an extension of MCNP for the transportation of all kinds of particles from electrons, more than 2000 heavy ions, and others. The code has a wide range of applications from medical physics, and nuclear engineering to radiation shielding.

MCNPX model radiation transport in matter tanking in count the MC method; the hole particle beam is divided in one history for each particle. The particle history contains not only the full particle track and information but also the same data for all the secondary particles produced until the annihilation of the original particle.

In order to get the information wanted from the simulation, the MCNP has the tally cards; this card can measure all kinds of magnitudes in the location provided. For radiation shielding the tally F5 is used, this tally determines the average of the energy deposition of the particle in its position (Pelowitz, 2011). The dose rate is calculated using the energy deposition obtained due to tally F5 and the multiplication factors presented in table 3, where FM is the multiplicity factor.

Table.3: Conversion factors to μSv/h

	CT	**SPECT**
FM	7.862E10	3.6E4

Results and Discussion.

In this work, a preclinical SPECT-CT system is modeled and the dose rate contribution is obtained for both of the two components of the equipment. Preclinical equipment is only used for research and the dose rate limit for occupationally exposed workers is 2.3 μSv/h. In figure 8 (left) there is a two-dimensional representation of the geometry of the equipment, the red points

represent the tally position where the dose rate was measured and the numbers are the distance in cm from the center of the mouse. figure 8 (right) shows a three-dimensional representation of the simulated geometry. In figure 9 the photons (blue lines) and the secondary electrons (green lines) tracks are shown for the SPECT (left) and CT (right) components of the equipment. Images 8 and 9 were obtained from the software vised61_24j.59.

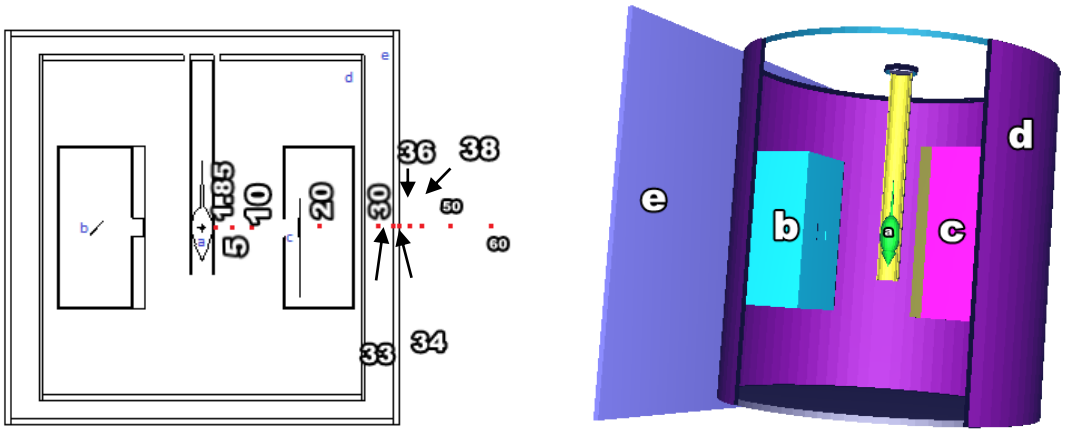
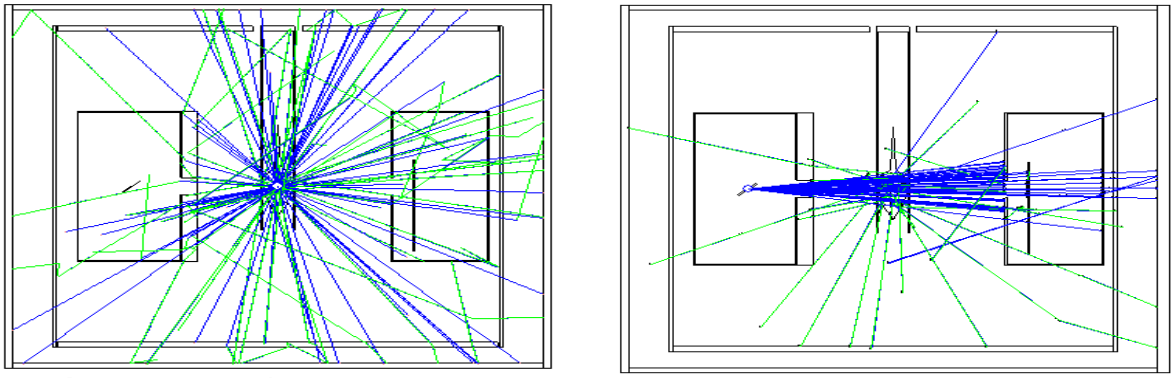


Fig.8: 2D (left) and 3D (right) Geometry representation.
a) Mouse **b)** X-ray Tube **c)** Detector **d)** Gantry wall **e)** Lead Wall.



a) SPECT tracks **b)** CT tracks

Fig.9: Photons and Secondary electrons tracks.

SPECT

Figures 10 to 12 show the plots, using the software Origin Pro 9, of the dose rate in μSv/h vs the distance from the patient in cm; and the different lines in each figure correspond to the different lead wall thickness studied, with a red line for dose rate limit for occupationally exposed workers.

Figure 10 corresponds to ^{99m}Tc and the intercept with the limit dose line is marked in the figure with a value of 22.31 cm for each of the lines more than 10 cm before the lead wall and just after the detector, this can be interpreted as almost all the radiation is absorbed before the detector or in the mouse body.

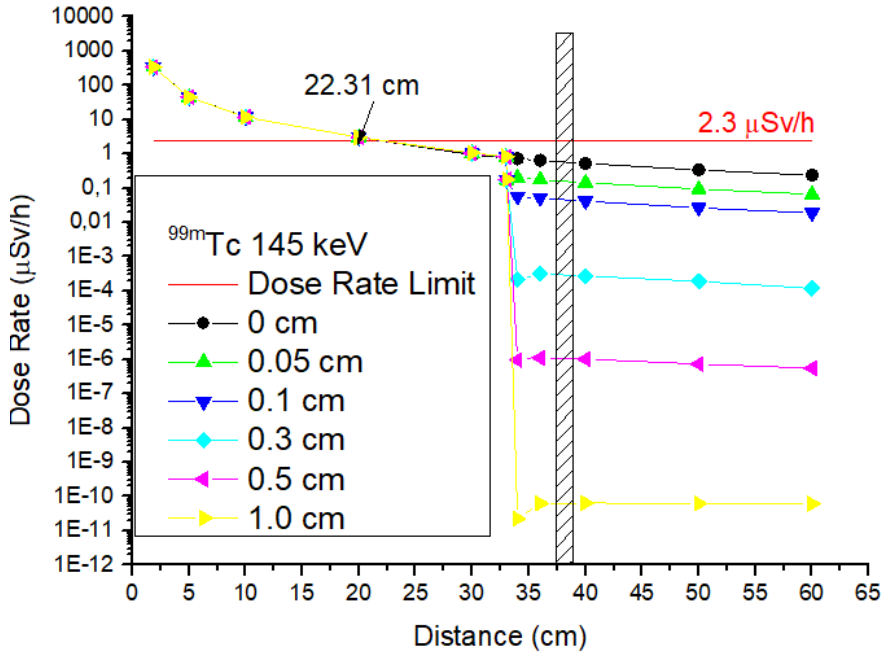


Fig.10: SPECT: Plot of Dose rate (^{99m}Tc) vs Distance for the different thickness of lead wall.

Something similar can be said from figures 11 and 12 corresponding to ^{123}I and ^{133}Xe, but with different intercept values of 23.66 cm (^{123}I) and 17.57 cm (^{133}Xe). The greater difference between the three isotopes is in ^{133}Xe which presents an intercept significantly lower with respect to the other two, but this can be simply explained by taking into account the energy of the photons emitted in the disintegration of the nucleus, the ^{133}Xe emits at nearly half the energy comparing with the other isotopes.

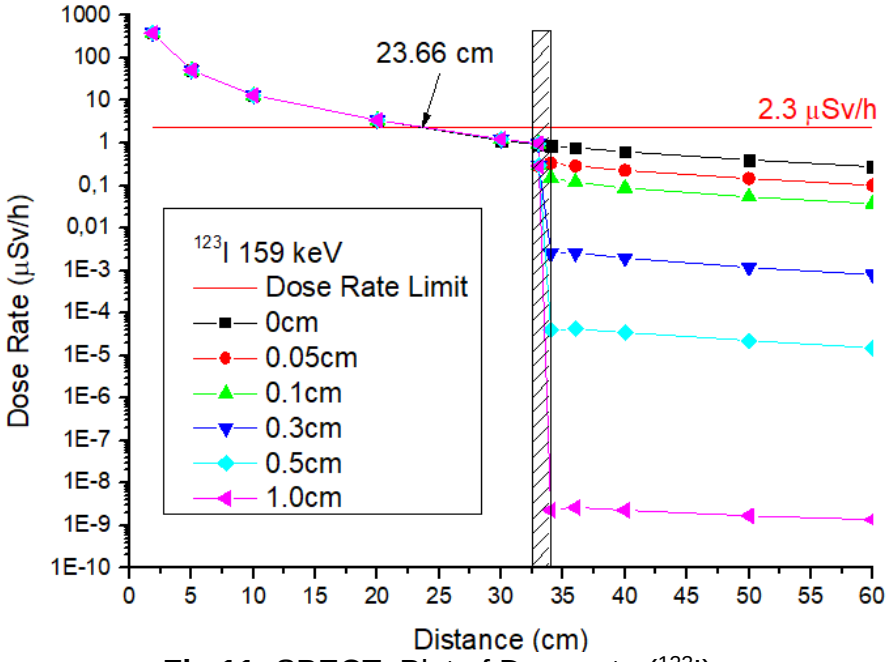


Fig.11: SPECT: Plot of Dose rate (^{123}I) vs Distance for the different thickness of lead wall.

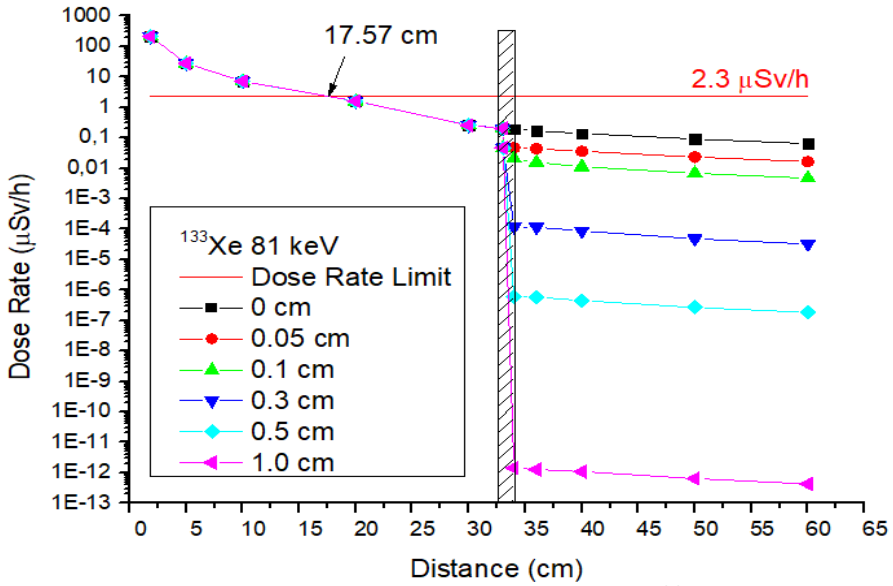


Fig.12: SPECT: Plot of Dose rate (^{133}Xe) vs Distance for the different thickness of lead wall.

CT

In figure 13 the plot of dose rate vs distance can be found for the CT component of the equipment. From the graphic it is simple to notice that the thicknesses of 0, 0.05, and 0.1 cm are not recommendable as shielding because the size of the facility was the equipment is going to be used will be extremely large from 8 to 36 m in radius approximately. A more viable shielding thickness will be 0.3 cm but only compared to the previous three; in fact, the 76 cm for this wall thickness is not relevant compared with others studied.

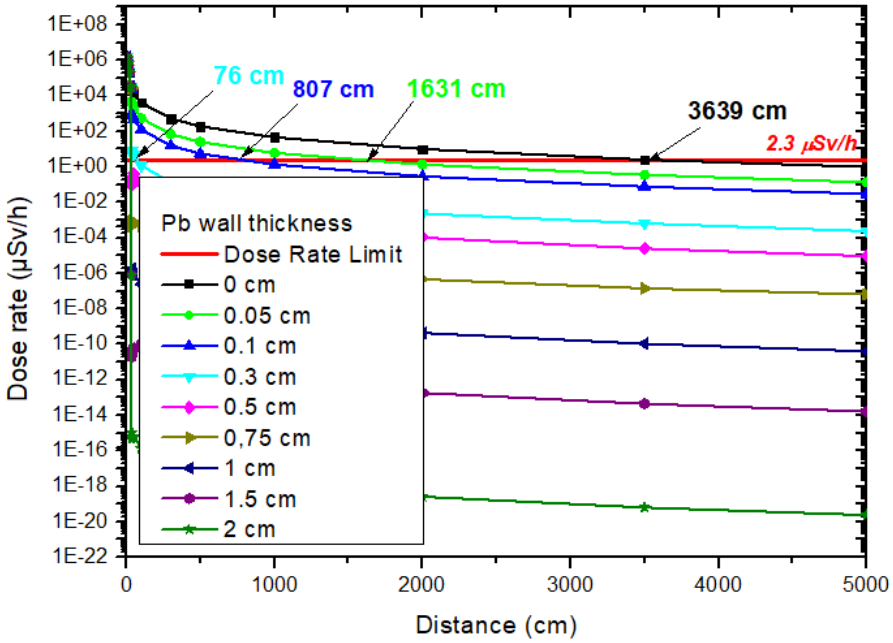


Fig.13: CT: Plot of Dose rate vs Distance for the different thickness of lead wall.

Lastly in figure 14 is visible a zoom version of figure 13, this is useful for a detailed analysis of the 0.5 cm and forward thicknesses. As can be found in the next figure the intercept values for the thickness between 0.5 and 2 cm are pretty close to each other with a maximum difference of 0.4 cm which represents approximately 1 % of intercept values. With this small difference, the most efficient value of the lead wall thickness will be 0.5 cm. Also, the intercept of 0.5 cm thickness is located outside of the lead wall which goes from 33 to 33.5 cm and the intercept value is 33.75 cm. The other intercepts are found inside the wall.

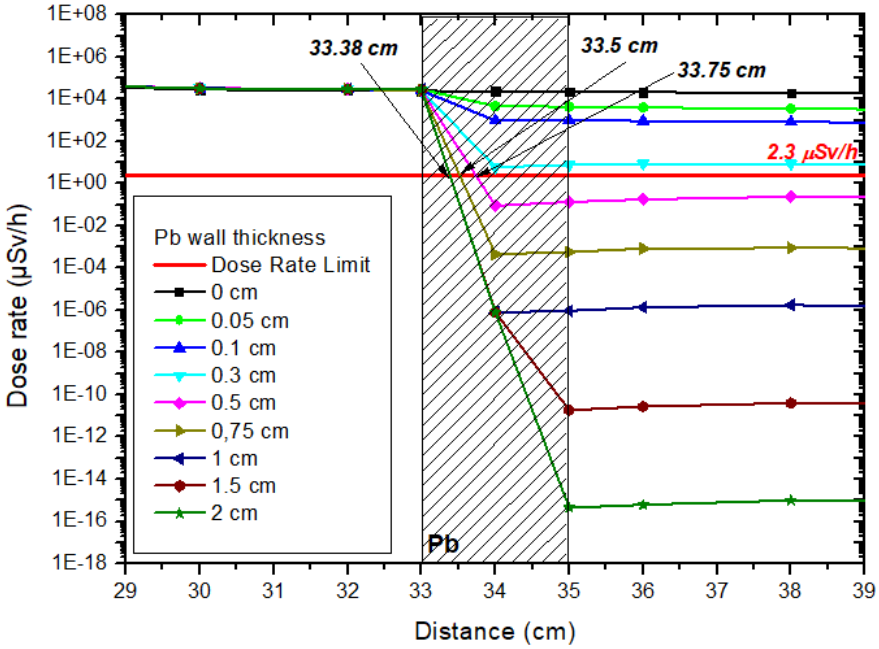


Fig.14: Zoom CT: Plot of Dose rate vs Distance for the different thickness of lead wall.

Table 4 shows the maximum amount of dose rate (touching the lead wall) received for the occupationally exposed work beyond the lead wall for comparison.

Table.4. Thickness vs Maximum dose rate received.

Thickness (cm)	**Maximum dose rate (µSv/h)**
0.75	3.6E-2
1	9.25E-7
1.5	2.21E-9
2	5.02E-16

Conclusions.

The Monte Carlo N-Particle code is a useful tool for the simulation of radiation transport, especially for dose rate calculation due to tally F5 and a simple multiplication factor for the conversion. In the program, a preclinical SPECT-CT hybrid system was modeled and run with the MCNPX code. The individual simulation of the SPECT and CT components, separately, was repeated for a range of thickness for the lead wall from 0 to 2 cm maximum and the sources used were a set of most common isotopes (^{99m}Tm, ^{123}I, ^{133}Xe) used for SPECT analysis and X-ray tube with a tungsten anode for CT.

From the software, vised61_24j.59 obtained the visual representation of 2D and 3D dimensions of the simulated geometry. Also, with the same program, the track representation of the photons and secondary electrons was visualized for SPECT and CT arrangements.

The lead wall thickness was determined for the SPECT and CT components using the intercept with the dose rate limits line of 2.3 µSv/h.

In the SPECT arrangement was studied some of the isotopes used in the radiopharmaceuticals as a source in the SPECT studies; for ^{99m}Tm the safe distance is 22.31 cm, for ^{123}I is 23.66 cm, and for ^{133}Xe is 17.57 cm. All the thickness values are inside the lead wall and the gantry, this makes a lead wall for the shielding of these isotopes.

The CT arrangement shows a different history with respect to SPECT, all the intercept values are inside or beyond the lead wall. This proves the importance of shielding in CT analysis. For 0.5 cm of wall thickness, the intercept is found short after the lead wall which represents a radiological risk for the equipment operator. From 0.75 cm of thickness and beyond the intercepts is inside the lead wall and the maximum dose rate received is 3.6E-2 µSv/h approximately 1.5 % with respect to the dose rate limit for occupationally exposed workers; this value makes sure that is not necessary to increase the wall thickness.

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