JOINT INSTITUTE FOR NUCLEAR RESEARCH
Laboratory of Nuclear Problems

FINAL REPORT ON THE INTEREST PROGRAMME

Study of radiation shielding in a preclinical SPECT/CT scanner using based on Monte Carlo code systems

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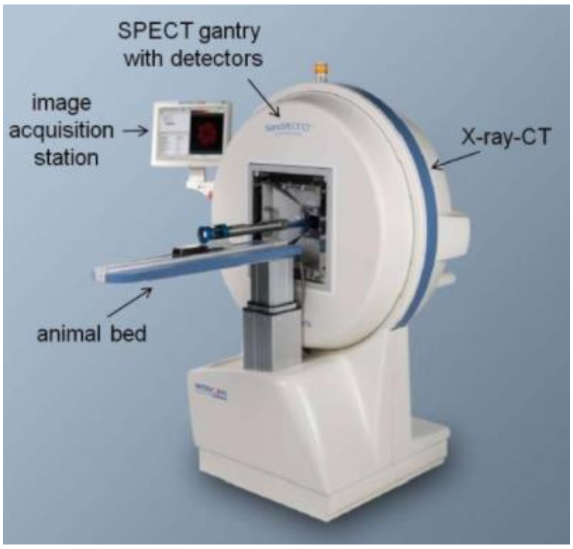
Abstract

This work studies the behavior of the Dose Rate vs Distance distributions for SPECT and CT scanners, individually; to investigate the characteristics regarding the radiation shielding in the SPECT/CT single multimodality instrument. Two Monte Carlo based code systems (MCNPX and GEANT4) were used to virtually simulate the hybrid equipment and study the interaction of radiation with matter. In simulations were taken into account the main geometric characteristics of the system under study, the materials that compose it and the different radiation sources: ^{201}TI, ^{99m}Tc and ^{131}I for SPECT, and a Roentgen tube for CT. This pages report the minimum safe distance, from the source, for an occupationally exposed worker for all four sources, in absence of any protective wall. The inclusion of a protective walls arrangement revealed that, for all 3 radioisotopes studied, in a preclinical SPECT intrument, the presence of protective walls is not strictly required. For the X-rays emitting source of CT configuration, the minimum safe distance, in absence of any wall, was large enough to ignore some protective barrier. The presence of protective walls, specially the lead wall, diminish the minimum safe distance from 7580.48 cm to 245.28 cm. This work also reports the analysis of the radiation attenuation percentage, at a certain distance, for both (SPECT and CT), for the lead wall belonging to the protective walls arrangement. The experimental findings indicate that a preclinical SPECT/CT scanner, with the characteristics considered here, needs the protective walls arrangement to attenuate X-rays radiation; but this is not sufficient to comfortably operate with this instrument. Some other mechanisms of radiation shielding must be taken into account.

Introduction

Radiation protection, is defined by the International Atomic Energy Agency (IAEA) as "The protection of people form harmful effects of expure to ionizing radiation, and the means for achieving this" [1]. Exposure can be from a source of radiation external to the human body or due to internal irradiation caused by the "ingestion" of radioactive contamination.

(a)



(b)

Figure 1. Example of a preclinical SPECT/CT scanner [2]: (a) – overview of the NanoSPECT/CT, Bioscan, USA, and (b) – main parts of the scanner.

Fundamental to radiation protection is the avoidance or reduction of dose using the simple protective measures of time, distance and shielding. The duration of exposure should be limited to that necessary, the distance from the source of radiation should be maximised, and the source shielded wherever possibe. This work, as indicated in the title, studies the role and importance of radiation shielding in a preclinical SPECT/CT scanner (figure 1).

Due to the serious consequences radiation could cause on any person exposed to it, is crucial to know exactly the doses to which workers and other perssonel will be exposed.

In this regard, virtual simulations of the experiment using a mathematical modeling of radiation transport suits perfectly to run simulations in conditions close to reality. This allows taking the necessary measures to ensure that the operation of a certain facility is safe.

Materials and Methods

SPECT/CT tomography

Single Photon Emission Computed Tomography (*SPECT*) is a nuclear tomographic imaging technique using gamma rays. It is very similar to conventional nuclear medicine planar imaging using a gamma camera, [3] but is able to provide true 3D information. This information is typically presented as cross-sectional slices through the patient, but can be freely reformatted or manipulated as required.

The technique needs delivery of a gamma-emitting radioisotope (a radionuclide) into the patient, normally through injection into the bloodstream. On occasion, the radioisotope is a simple soluble dissolved ion, such as an isotope of gallium. Most of the time, though, a marker radioisotope is attached to a specific ligand to create a radioligand, whose properties bind it to certain types of tissues. This marriage allows the combination of ligand and radiopharmaceutical to be carried and bound to a place of interest in the body, where the ligand concentration is seen by a gamma camera.

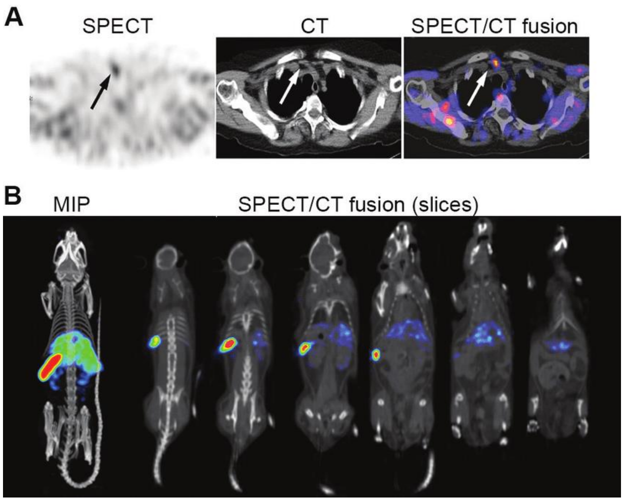


Figure 2: Examples of two SPECT/CT imaging applications: (A) – clinical, and (B) - preclinical applications; both showing at right the fused SPECT/CT slices. Adapted from [5,6].

In some cases, a SPECT gamma scanner may be built to operate with a conventional CT scanner, with coreregistration of images. CT stands for “computed tomography”, and refers to a computerized X-ray imaging procedure in which a narrow beam of X-rays is aimed at a patient and quickly rotated around the body, producing signals that are processed by the machine’s computer to generate the cross-sectional images, or “slices”, of the body[4]. These slices are called tomographic images and contain more detailed information than conventional X-rays. Once several successive slices are collected by the machine’s computer, they can be digitally “stacked” together to form a three-dimensional image of the patient that allows for easier identification and location of basic structures as well as possible tumors or abnormalities.

The SPECT/CT hybrid technique, allows the location of tumors or tissues, which may be seen on SPECT scintigraphy, but are difficult to locate precisely with regard to other anatomical structures [7] . Such scans are most useful for tissues outside the brain, where the location of tissues may be far more variable.

Figure 2 shows with two examples the capabilities of imaging applications, both clinical and preclinical. As can be seen, the fusion of the images obatined by the two techniques has a superior quality in all possible aspects.

Dose limits

The dose limits are recommended by the International Commission on Radiological Protection (ICRP). They ensure that individuals are not exposed to an unnecessarily high amount of ioning radiation and breaching these limits is againgst radiation regulation in most countries.

The limits are split into two groups, the public, and occupationally-exposed workers. Table 1 contains the dose limits per year, for occupationally exposed workers (a person who is exposed to radiation while pursuing their profession or being trained) and public, for the body parts, including the whole body itself [8].

Table 1: Dose limits per year for different human groups.

	Occupationally exposed workers	**Public**
The entire body - effective dose	20 mSv	1 mSv
Equivalent dose to the lens of the eye	20 mSv	15 mSv
Equivalent dose to the skin	500 mSv	50 mSv
Equivalent dose to hands and feet	500 mSv	50 mSv

Geant4 / MCNPX

The Monte Carlo method is essentially in its approach: a numerical solution to a macroscopic system through simulation of its microscopic interactions. A solution is determined by random sampling of the relationships, or the microscopic interactions, until the result converges. Thus, the mechanics of executing a solution involves repetitive action or calculation. There are many examples of the use of the Monte Carlo method, not only in physics and science, but also in traffic flow, finance, population growth, social studies, etc.[9]

Two of the most well-known softwares, utilizing the Monte Carlo method to produce the more realistic calculation codes for particle transport and interaction with matter, are GEANT4 and MCNPX.

MCNP is a general-purpose, continuous-energy, generalized geometry, time-dependent Monte Carlo radiation transport code designed to track many particles types over broad ranges of energies [10]. It is the next generation in the series of Monte Carlo transport codes that began at Los Alamos National Laboratory. MCNPX (Monte Carlo N-Particle eXtended) is capable of simulating particle interactions of 34 different types of particles (nucleons and ions) and 2000+ heavy ions at nearly all energies, including those simulated by MCNP. Specific areas of application include, but are not limited to, radiation protection and dosimetry, radiation shielding, radiography, medical physics, nuclear criticality safety, detector design and analysis, nuclear oil well logging, accelerator target design and analysis, fission and fusion reactor design, decontamination and decommissioning. The code treats an arbitrary 3D dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori [11].

Written in Fortran, it is fundamentally based on the use of the effective section of each type of interaction and the statistical nature of the transport process to predict the probability of distribution of specific parameters such as energy losses and angular detection.

GEANT4 (for GEometry ANd Tracking) is a platform for “the simulation of the passage of particles through matter” using Monte Carlo methods [12]. It is the successor of the GEANT series of software toolkits developed by the Geant4 collaboration, and the first to use object oriented programming (in C++). Applications areas include high-energy physics and nuclear experiments, medical, accelerator and space physics studies.

GEANT4 includes facilities for handling geometry, tracking, detector response, run management, visualization and user interface. For many physics simulations, this means less time needs to be spent on the low-level details and researches can start immediately on the more important aspects of the simulation.

In the present work, both softwares were used to simulate the interaction of radiation with matter, with the aim of studying the characteristics of the radiation shielding in a preclinical SPECT/CT scanner prototype. In the simulation, the most important components of the scanner, with their typical material and dimensions, will be taken into considerations.
To ensure that the relative statistical errors of the simulations results carried out in this work are as low as possible, in each simulation, a large number of stories was used (1e7).

Sources

A typical SPECT/CT scanner uses two different radiation sources: a gamma-emitting radioisotopic source and an X-ray tube. For the SPECT setup, in this work a 10 MBq activity gamma point source placed inside the mouse, exactly in its center, was employed. Three of the radioisotopes most used in SPECT imaging were studied. They are shown in Table 2, alongside their energies.

The source of the CT configuration consists of a Roentgen tube, which in the simulation of this work for simplicity is replaced by a point source. This source emits towards the target within a 20º cone and strictly with the characteristic spectrum of the tungsten anode (W). The tube acceleration potential of 120 keV and a current of 350 μA were taken into account to determine the number of photons emitted by the source.

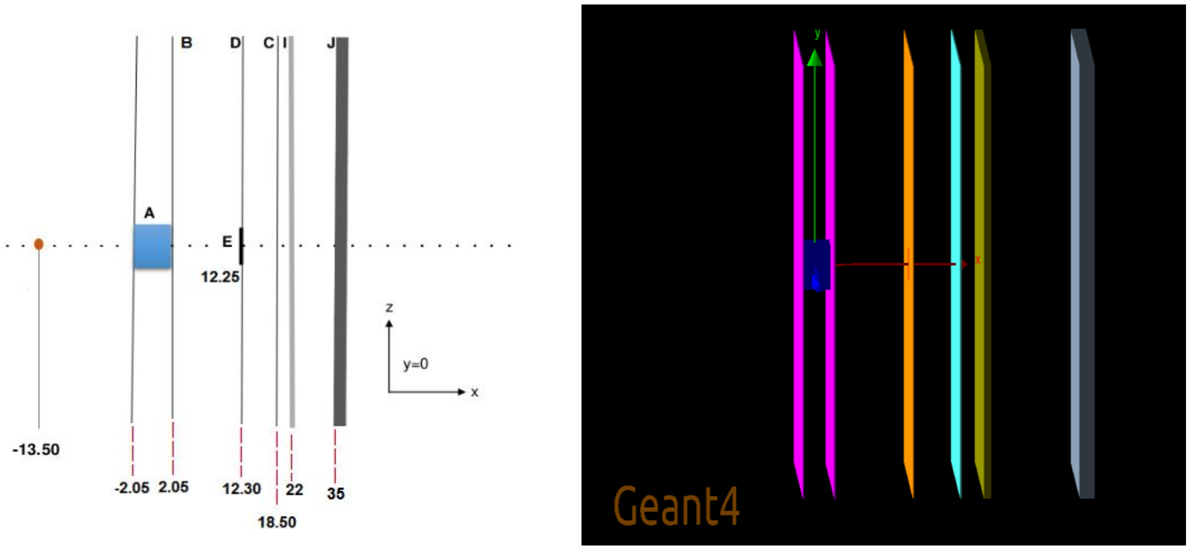
Table 2: Table of the chosen radionuclides and their energy.

No.	Radionuclide	Eγ [keV]
1	^{201}Tl	70
2	^{99m}Tc	140.5
3	^{131}I	364

Results

SPECT

The simplest geometry of the SPECT arrangement appears in figure 3. The image was taken from the visual environment of GEANT4.



(a) (b)

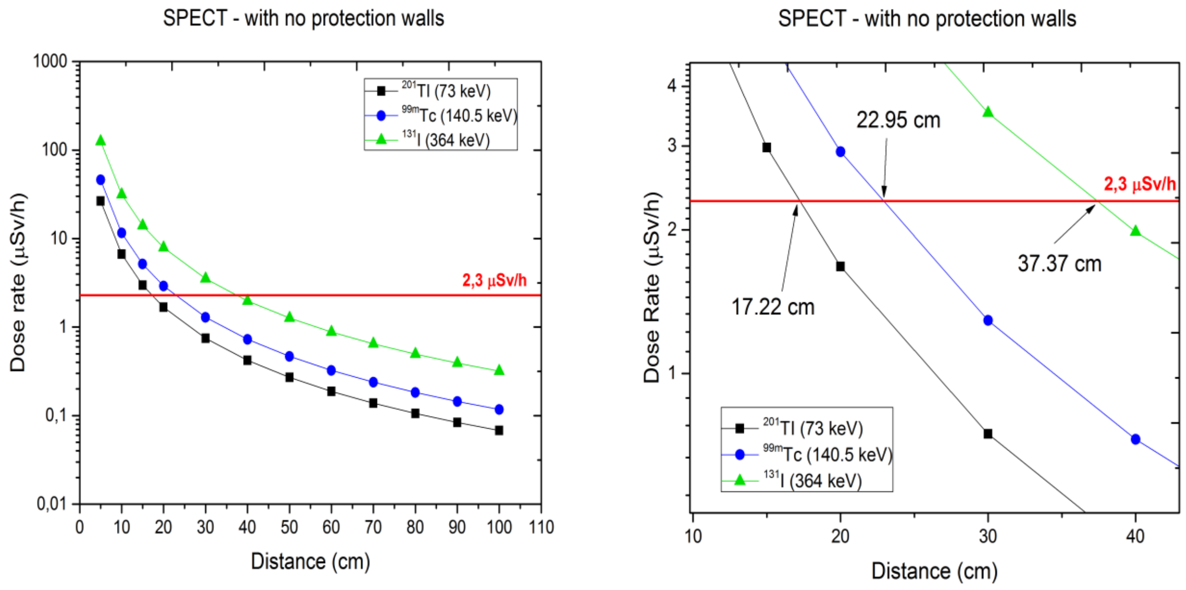
Figure 3: Schematic representation of the SPECT geometry for current simulation experiment. Image (a) identifies each component of the arrangement, alongside its position in space (cm); while (b) represents the final construction using GEANT4 facilities.

In this configuration, figure 3, component A represents the target mouse. B stands for the polypropylene walls of the bed where the mouse is located. Following the order, E is a 500 µm GaAs:Cr detector, D is a fiberglass support for the detector, C is a stainless 202 wall (part of the protective case), I is the duralumin gantry and J is a wall of lead (Pb).

The red dot to the left of the mouse indicates the position of the X-rays source. In figure 3 (b), the components have the same order but with different colours, to make it visualy understandable.

In order to evaluate the behavior of the dose rate with distance, for each selected source, using the MCNPX software, some point detectors were placed along the X axis to measure the fluence of the particles at selected distances from the source and phantoms. The obtained fluence magnitudes are converted to dose magnitudes by implementing some MCNPX facilities in the simulation input file. Finally, the graphs of the dependencies of Dose Rate vs Distance for each experiment are constructed.

Figure 4 shows the dependence of the dose rate with the distance for the 3 radionuclides studied, when none of the protective walls have been considered. In figure 4 and the others that will be presented hereinafter, the dose rate limit considered safe for occupationally exposed workers is represented by a red line, allowing determine the minimum safe distance with respect to the position of the source. Table 3 contains this information for current experiment.



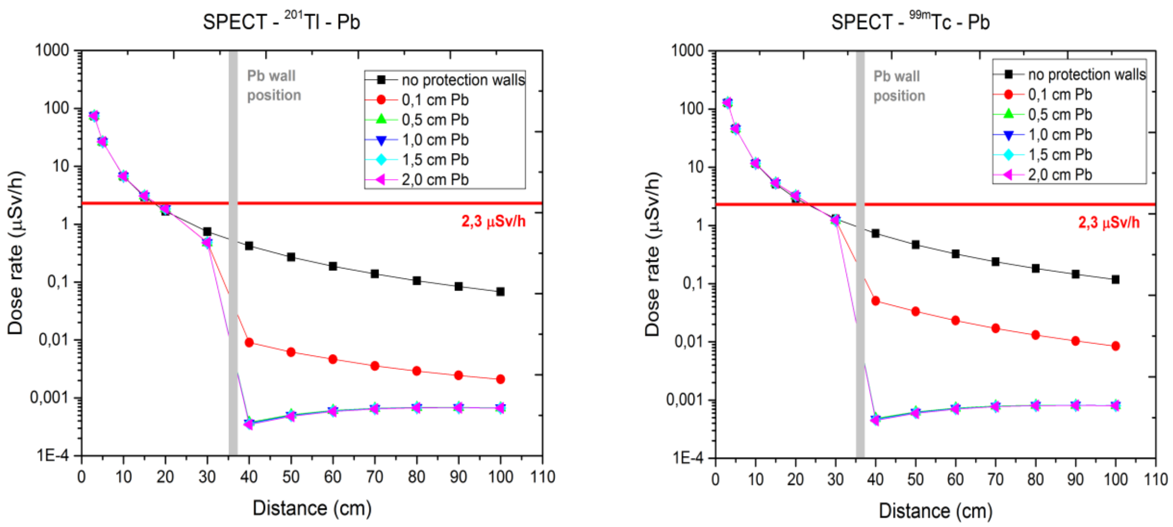
(a) (b)

Figure 4: Dose Rate vs Distance behavior for ^{201}Tl, ^{99m}Tc and ^{131}I radioisotopes without any protection wall (a), and a zoom to region of interest of the same graph (b).

Table 3: Secure distance from the source for occupationally exposed workers.		
Radionuclide	**Eγ (keV)**	**Minimum safe distance (cm)**
^{201}Tl	70	17.22
^{99m}Tc	140.5	22.95
^{131}I	364	37.37

The values presented in table 3 indicate the minimum distances from the source, for each of the 3 isotopes selected, that any occupationally exposed worker must follow to not exceed the limit dose of 20 mSv per year, or around 2.3 mSv per hour. The purpose of this is to provide an appropiate level of protection for humans without unduly limiting the beneficial actions giving rise to radiation exposure. Therefore, in absence of walls that can attenuate gamma radiation, is essential to comply with the minimum safe distances protocol.

Now, the results of the simulations, considering all different walls, for all the radioisotopes selected, are shown in figure 2. Is expected that the presence of the Pb wall causes a great effect upon the radiation coming out of each radionuclide.



(a) (b)

Figure 5: Dose Rate vs Distance behaviours for 201Tl (a), and 99mTc (b) sources. Each curve corresponds to a certain Pb wall thickness.

Figure 5, corresponding to ^{201}Tl and ^{99m}Tc sources, show that although they have a safe distance located before the Pb wall position (35 cm), is significant the attenuation effect the Pb wall has, even for small thickness of it. The Pb wall of 0.1 cm of thickness, 40 cm of distance from the source, weakens the radiation in a 98% and 95% for ^{201}Tl and ^{99m}Tc, respectively. Greater thicknesses increases the attenuation effect up to 99.9% for both sources.

For the ^{131}I source, see figure 6, 0.1 cm of Pb wall causes a radiation attenuation of 61.2%, but with 1.0 cm it already reaches 97.2% and with 1.5 cm or more, the attenuation becomes greater than 99.2%.This information is presented in Table 4.

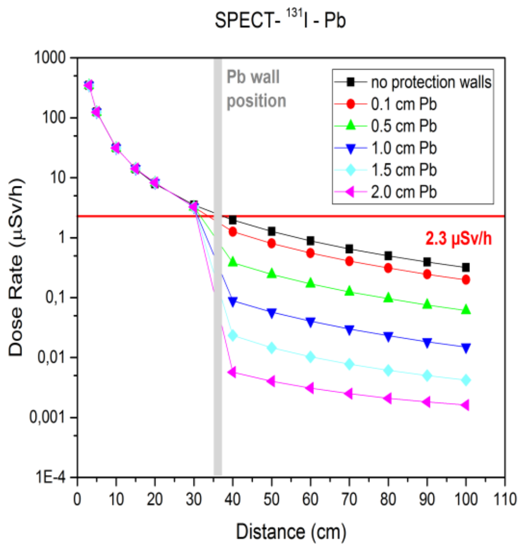
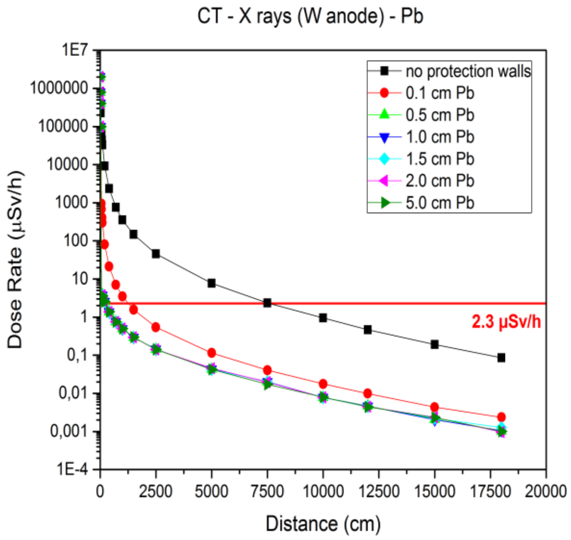


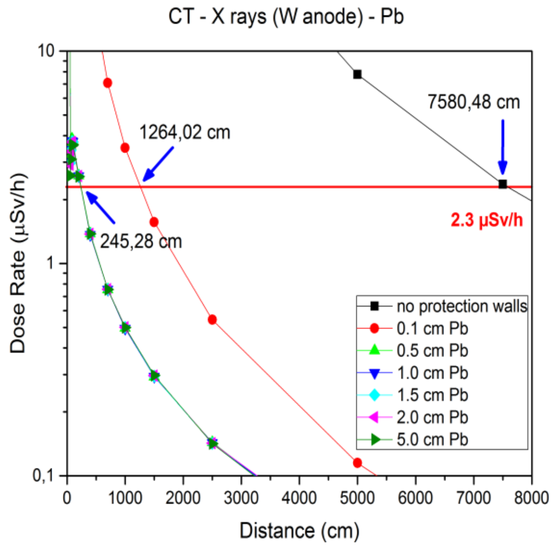
Figure 6: Dose Rate vs Distance for ^{131}I source. Each curve corresponds to a certain Pb wall thickness.

Table 4: Attenuation percentage of the radiation, caused by the Pb wall protection shield, obtained for 40 cm of distance from the source, for each radionuclide studied.			
Thickness (cm)	**Attenuation (%)**		
	^{201}Tl	^{99m}Tc	^{131}I
0.1	98.123	95.882	61.266
0.5	99.921	99.961	88.195
1.0	99.924	99.962	97.253
1.5	99.926	99.962	99.278
2.0	99.928	99.964	99.824

CT

As observed in figures 7(a) and 7(b), which show the Dose Rate vs Distance behaviour for the X-rays source with different Pb thickness, in absence of any protection wall, the minimum safe distance with respect to the center of the mice is 7537. 619 cm. This value is large enough to pay special attention to, in order to guarantee the staff safety.





(a) (b)

Figure 7: Dose Rate vs Distance for the X-rays source and different thickness of the lead wall (a), and a zoom to region of interest of the same graph (b).

With no protection walls, at a distance of 30 cm from the center of the mice, 43.5 cm of distance from the X-rays source (see figure 2), the radiation experiences a 88.5% of attenuation. The fiberglass, stainless 202 and duralumin walls attenuate the radiation in a 95.02%, although the dose rate at this position stills being greater than 2.3 mSv/h. Therefore, this walls are not sufficient for the CT part of the scanner to attenuate the radiation to the desired level.

Once the Pb wall is inserted, the minimum safe distance diminish significatively (see figure 7 (b)). Compare to the other 3 sources, for 0.1 cm of Pb wall , the minimum safe distance is now 1264.02 cm; while for greater values of thickness, the minimum safe distance decreases to 245.28 cm.

The attenuation of radiation observed, at a distance of 55 cm from the center of the phantom, was 98.96% for 0.1 cm of lead wall; and 99.99% for the rest of the thicknesses studied (see Table 5). These results reveal that there is a maximum thickness value above which increasing this value has no effect on radiation. Table 5 shows how 0.5 cm of thickness is enough to attenuate radiation in a 99.99%.

Table 5: Attenuation percentage of the radiation, caused by the Pb wall protection shield, obtained for 55 cm of distance from the source, for the X-rays tube.

Thickness (cm)	Attenuation (%)
0.1	98.958
0.5	99.997
1.0	99.997
1.5	99.997
2.0	99.997
5.0	99.997

Conclusions

The purpose of this work was to study the radiation shielding of a preclinical SPECT/CT scanner using Monte Carlo methods for particle transport and interaction with matter. MCNPX was the main software selected to run the experiment, with the support of GEANT4 software too. The scanner uses two different radioactive sources: a gamma-emitting radiation source and a X-rays emitting source. Both kind of sources were analysed obtaining the dose rate dependence with the distance for three well-known radioisotopes (^{201}TI, ^{99m}Tc, ^{131}I) and a X-ray tube.

For the SPECT configuration, the analysis of the Dose Rate vs Distance, for all three radioisotopes, in absence of any radiation shielding, allowed determining the minimum safe distance for occupationally exposed workers to guarantee no harmful effects on their health due to radiation exposure. The presence of the protective walls arrangement made no considerable differences on the minimum safe distance for all three sources; remaining this 17.22, 22.95 and 37.37 cm for ^{201}TI, ^{99m}Tc and ^{131}I, respectively. Hence, for these radioisotopes, it is posible to construct a simple preclinical SPECT device where no protection walls are considered since the safe distance from the source, for an occupationally exposed worker, is small enough to operate and guarantee his safety without the lead wall.

A different analysis of the dose rate at a certain distance, before and after the position of the wall, revealed that for ^{201}TI and ^{99m}Tc, 0.1 cm of thickness of lead wall attenuates the radiation in a 98 and 95%, respectively; while for ^{131}I, 1.0 cm of thickness of wall is necessary to reach 97% of radiation attenuation.

The Dose Rate vs Distance for CT configuration, in absence of any protection wall, showed a minimum safe distance of 7537.62 cm. The inclusion of a lead wall of 0.1 cm attenuates the radiation a 98.96% and 0.5 cm of thickness increases attenuation up to 99.99%, diminishing the minimum safe distance to 245.28 cm. This results revealed that, for the X-rays source studied, there is a maximum thickness value above which increasing this value has no effect on radiation attenuation. This value is 0.5 cm.

Considering the results obtained for SPECT and CT configurations individually, it is safe to say that in a preclinical SPECT/CT arrangement, with the characteristics presented here; it is indispensable but not sufficient, the presence of a lead wall of 0.5 cm of thickness to attenuate X-rays radiation corresponding to the CT part of the arrangement. But, a distance of 245.28 cm is still large enough to operate with such small device. Therefore, some other mechanisms of radiation shielding should be considered.

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