JOINT INSTITUTE FOR NUCLEAR RESEARCH

FINAL REPORT ON THE INTEREST PROGRAMME

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

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Abstract

Radiation can be used by medical physics for multiple purposes. Their advances in health have been remarkable. At the same time, awareness has been open when thinking about the risk it constitutes for occupationally exposed personnel. In this research, was studied the radiation dose distribution around a preclinical CT and SPECT techniques, using different radiation sources. It was seen how the inclusion of a lead wall that serves as shielding complement to the system, influences the dose rate. Mathematical simulations of all different geometric arrangements were made using Monte Carlo method based MCNPX code system. The results were processed using the ORIGIN software. The curves of the dose rate with the distance dependences for different lead wall thicknesses were compared to the internationally recognized limit of safe dose (2.3 μSv/h), which made it possible to determine for each studied case the minimum safe distance for operating with these techniques peoples. In the text, this results obtained are presented graphically and analyzed.

Introduction

All devices that in their operation use some source of ionizing radiation must necessarily guarantee the health safety of all occupational personnel, patients, visitors, etc. Especially important are those diagnostic and medical treatment techniques that use ionizing radiation, such as common X -ray equipment, gamma cameras, CT, PET and SPECT scanners, etc. In the studies focused on the determination of the most optimal and safe radiological conditions for the exploitation of these systems, the mathematical modeling of radiation transport plays an important role. This is because, with its use, it is possible to carry out the simulation experiments in the most realistic way possible and allows to calculate with great precision, not only the doses distribution, but also some hard to measure parameters, quickly and economically.
In this Report, with the use of mathematical simulation, was calculated the distribution with the distance of the dose rate for different geometries and sources in the vicinity of a preclinical SPECT/CT. Using the results of the calculations, the lowest distance considered safe for health according to internationally recognized parameters will be estimated. The optimal thicknesses of the protective lead wall will also be evaluated in order to minimize the exposure doses.

Materials and Methods

SPECT/CT tomography

- **CT (Computed Tomography) or CAT (Computerized Axial Tomography)**

A CT scan is a diagnostic imaging procedure that uses X-rays taken from different angles around the body and uses computer processing to create cross-sectional images (slices) of the bones, blood vessels and soft tissues in the body, and diagnose disease or injury, as well as plan medical, surgical, or radiation treatment.

CT is based on the fundamental principle that the density of the tissue passed by the X-ray beam can be measured from the calculation of the attenuation coefficient, which allows the reconstruction of the density of the body, by two-dimensional section perpendicular to the axis of the acquisition system.

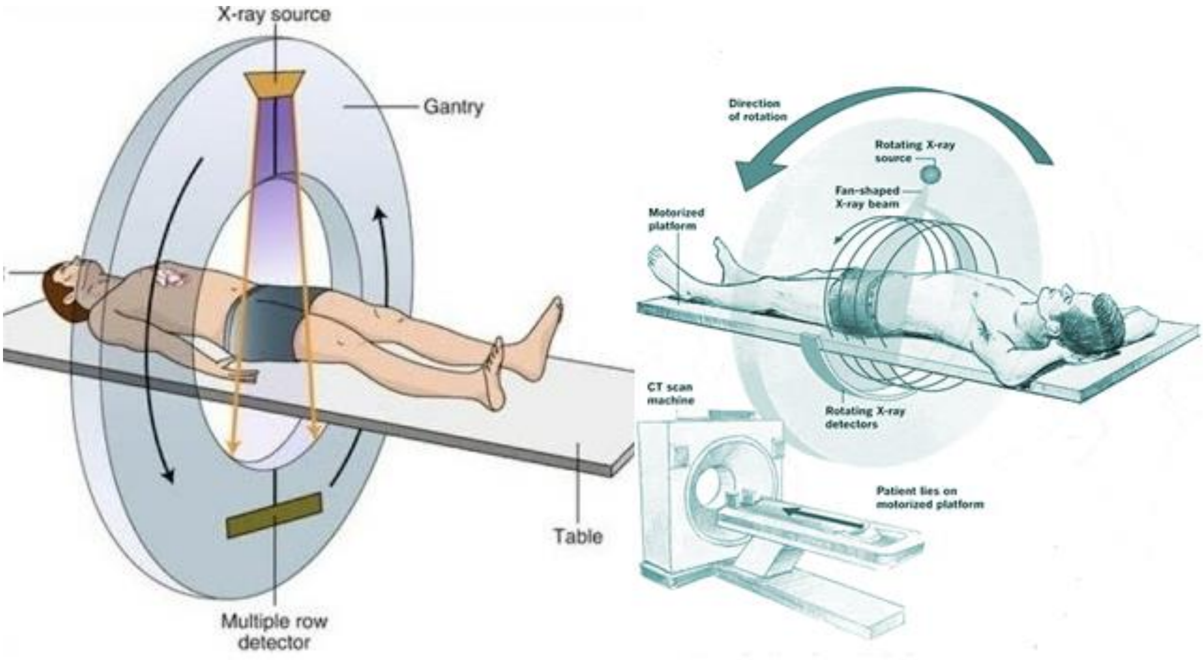

Fig. 1: Schematic representation of the CT scanner and its more important components.

Figure 1 shows a schematic representation of a CT scanner with its different fundamental parts. The CT X-ray tube (typically with energy levels between 20 and 150 keV), emits N photons (monochromatic) per unit of time. The emitted X-rays form a beam which passes through the layer of biological material of thickness Δx. A detector placed at the exit of the sample, measures $N + \Delta N$ photons, ΔN smaller than 0. Attenuation values of the X-ray beam are recorded, and data used to build a 3D representation of the scanned object/tissue.

In the particular case of the CT, the source of X-rays rotates around the patient and the detector, placed in diametrically opposite side, picks up the image of a body section (beam and detector move in synchrony). The detectors of the CT scanner do not produce an image. They measure the transmission of a thin beam (1-10 mm) of X-rays through a full scan of the body. In order to obtain tomographic images of the patient from the data in "raw" scan, the computer uses complex mathematical algorithms for image reconstruction [1].

- **SPECT (Single Photon Emission Computed Tomography)**

SPECT is a three-dimensional nuclear medicine imaging technique combining the information gained from scintigraphy with that of computed tomography. This allows the distribution of the radionuclide to be displayed in a three-dimensional manner offering better detail, contrast and spatial information than planar nuclear imaging alone. These machines combine an array of gamma cameras (ranging from one to four cameras) which rotate around the patient on a gantry. SPECT may be also combined with a separate CT machine in a form of hybrid imaging; single photon emission computed tomography-computerized tomography (SPECT-CT) mainly for the purposes of attenuation correction and anatomical localization.

Gamma cameras rotate around the patient providing spatial information on the distribution of the radionuclide within tissues. The use of multiple gamma cameras increases detector efficiency and spatial resolution. The projection data obtained from the cameras are then reconstructed into three-dimensional images usually in axial slices [2].

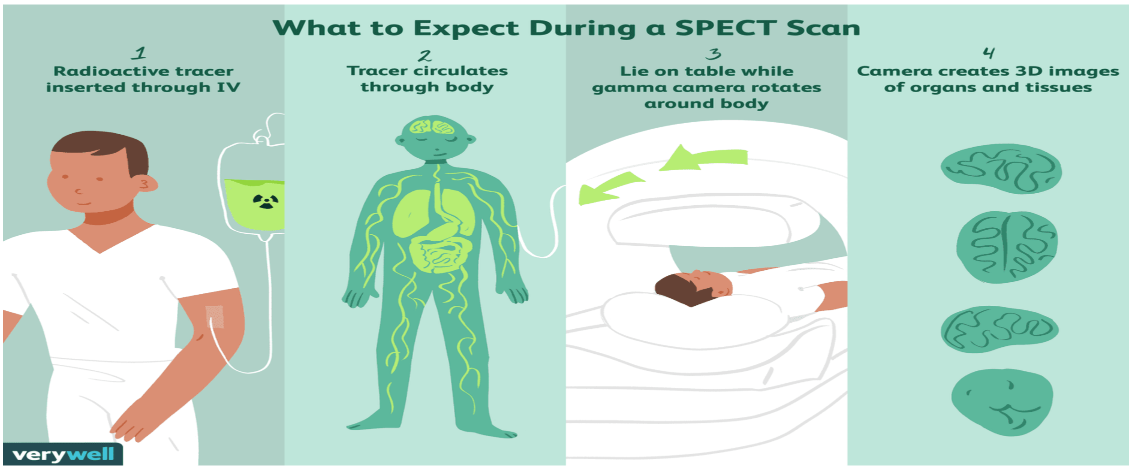

Fig. 2: Procedure during a SPECT scan.

Figure 2 shows the different stages a patient goes through when undergoing a SPECT scan, from the phase in which the radioisotope is introduced into the patient through the intravenous line until the 3D image is obtained. Is introduced a flat-panel X-ray detector for cone beam CT acquisition, which conveniently attaches to the SPECT gantry and produces good contrast images with isotropic voxels, well suited to the angular reorientation commonly used in nuclear medicine.

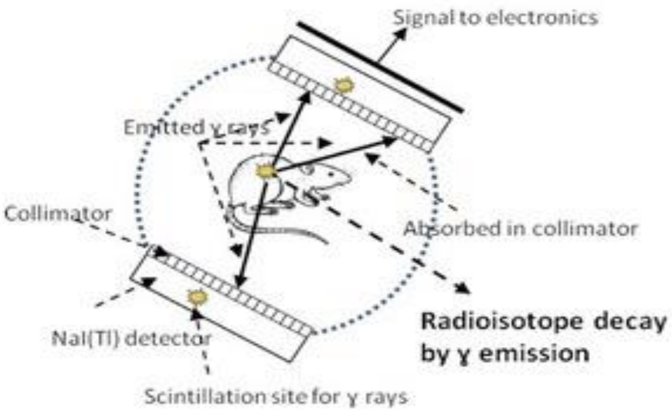

Fig. 3: Diagram of SPECT scanner.

The diagram of SPECT scanner, its components and representation of the emission and absorption of gamma rays, is presented in figure 3.

The combining SPECT CT scan decreases the scan time by 50 %, making it faster. As less time is required for the diagnostic test, the dose of radiopharmaceutical supplied to the patient is reduced in the same way, requiring less radiation. In addition, a better diagnosis is obtained compared to conventional equipment. These are the advantages of using this technique [3].

On the other hand, it is necessary to use a special system of rapid rotation around the patient. Another disadvantage is the poor spatial resolution and the presence of artifacts due to radioisotopes present in the nasopharynx (when the tracer is administrated by the inhalation). Also is contraindicated during pregnancy [4].

Sources

The most common material with which the anode of X-rays is made is Tungsten, due to its properties from the point of view of thermionic emission and high melting point. In the case of mammography tubes, the material used is Molybdenum, and recently they have also begun to make Rhodium-Palladium [5].

In our simulations a Tungsten Roentgen tube is used as source of X-rays. For simplicity in calculus, the anode in the X-ray tube was approximated to a point-like source positioned 1 mm in front of a hypothetical tungsten anode. Within a solid angle of 20°, this source emits only in the target direction.

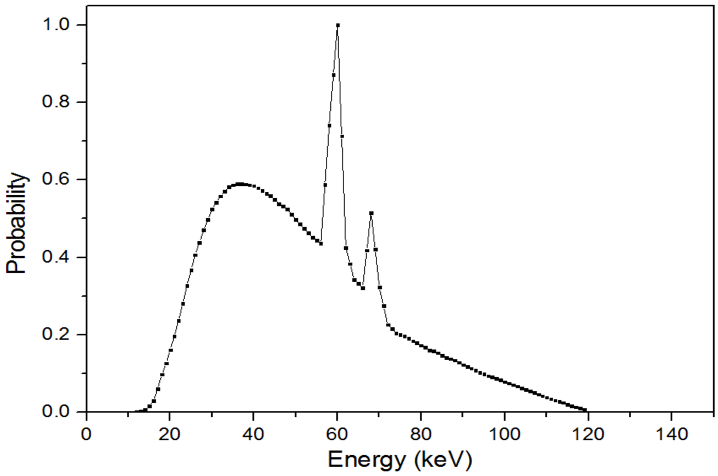

Fig. 4: Tungsten anode spectral model at 1 keV intervals.

The Tungsten anode spectrum is shown in figure 4.

There are many radioisotopes used in nuclear medicine, but the main isotopes used in the SPECT technique are: Xenon 133 and 127 (^{133}Xe,^{127}Xe), Technetium 99 (^{99m}Tc), Iodine 131 (^{131}I) and Thallium 201 (^{201}Tl); of these, the first four are chemically inert (they are not retained in the brain) and the last one is chemically active (they are retained in the brain). The most widely used are ^{133}Xe (administered by inhalation or intravenous route) and ^{99m}Tc [6]. In Table I the above-mentioned isotopes are related with their corresponding energy and half-life times.

Table I: List of the most common radioisotopes used in SPECT imaging and their main characteristics.

Radioisotopes	keV	Half-life
^{133}Xe	81	5.3 d
^{99m}Tc	140.5	6 h
^{131}I	364	8.04 d
^{201}Tl	68-82	73 h

Monte Carlo based code systems for modeling radiation transport in matter

The Monte Carlo method is a numerical solution to a problem that models objects interacting with other objects or their environment based on simple object-object or object environment relationships. It represents an effort to model nature through direct simulation of the essential dynamics of the system in question. The Monte Carlo method is essentially simple in its approach of a solution to a macroscopic system in this sense through the simulation of their microscopic interactions.

A Monte Carlo simulation can serve two purposes. Either it can provide a small correction to the theory, or it can be used to directly verify or disprove the theory of interactions. Monte Carlo techniques in this field are useful for predicting the trajectories of high energy particles through complex materials [7]. In Figure 5 can be seen the relationship between the theory, the experiment and Monte Carlo method, which constitutes a representation of its use.

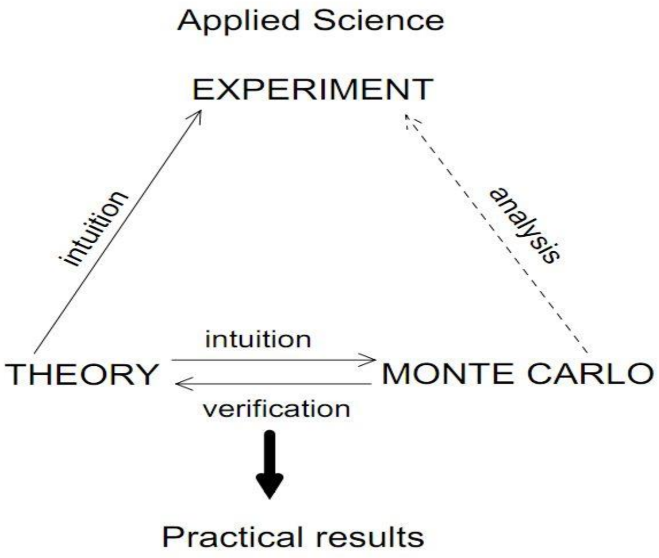

Fig. 5: Representation of the Monte Carlo method use.

Monte Carlo methods are often seen as a competitor to other macroscopic calculation methods called deterministic and/or analytical methods. The more complex the model to be developed, the use of Monte Carlo methods increases [8]. In figure 6 can see a graph that relates the complexity of a problem and the solution time used for them and serves to compare the Monte Carlo method and the analytical methods in terms of these parameters.

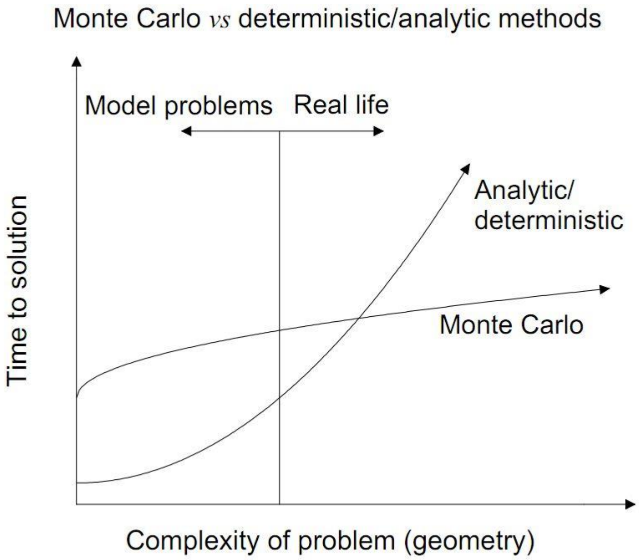

Fig. 6: Monte Carlo method vs. deterministic/analytic methods.

MCNP (Monte Carlo N-Particle Transport Code)

The MCNP code can be used for general purpose transport of many particles including neutrons, photons, electrons, ions, and many other elementary particles, up to 1 TeV/nucleon. Important standard features that make the MCNP code versatile and easy to use include a powerful general source, criticality source, and surface source; both a fixed source and k-eigenvalue solution mode; 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 application areas that use the predictions of the MCNP code include (but are not limited to): radiation protection and dosimetry, radiation shielding, radiography, medical physics, nuclear criticality safety, critical and subcritical experiment design and analysis, detector design and analysis, nuclear oil-well logging, accelerator target design, fission and fusion reactor design, decontamination and decommissioning, and nuclear safeguards and nonproliferation [9].

Dose safe limits

The objectives of the “Basic international safety standards for radiation protection against ionizing radiation and for the safety radiation sources” are to establish the requirements for the protection of people and environment against the harmful effects of ionizing radiation and for the safety of radiation sources. For the correct application of this system is design and operational activities, it is necessary to set numerical values of the various magnitudes that serve as a guide to know the type and form of protective measures required in a given situation. For this, the limits are those values established to prevent deterministic effects and guarantee a decrease in the detriment occurred associated with stochastic effects. These limits are in accordance with whether the person is exposed or not. They are categorized into occupationally exposed workers and members of the public (people who work or reside in premises close to occupationally exposed workers).

Normal exposure of individuals will be restricted so that the total effective dose and the total equivalent dose to major organs or tissues caused by the possible combination of exposures from authorized practices cannot exceed any major dose limit specified by the standard. These include exposure to external and internal sources; their values are given based on the biological effect they cause. They do not include natural or medical exposure, nor are they applied in the event of an accident at a source or due to an event or sequence of events of a probabilistic nature that includes equipment failures or operating errors [10]. In Table II appears the maximum permissible dose for different people, separated into three fundamental groups: occupationally exposed workers, the public and students.

Table II: Permissible dose limit for occupationally exposed personnel, the public and students.

	Occupational	**Public**	**Students 16-18 years old**
Effective dose	20mSv per year averaged over 5 years	1mSv/y in a year	6mSv/y
Equivalent dose in the lens	20mSv	15mSv/y	20mSv/y
Equivalent dose on the skin	500mSv/y	50mSv/y	150mSv/y
Equivalent dose to extremities	500mSv/y	-	150mSv/y

Results

SPECT

This task was executed using three radioisotopes: Thallium, Technetium and Iodine, the most used in medical procedures, in the case of SPECT. For each of these isotopes, as point sources positioned in the coordinate center (center of the target mouse), the behavior of the dose rate a with the distance from the source was analyzed. This was done for different thicknesses of the lead shielding wall located 33 cm from the source, in the range between 0 and 2 cm.

For Thallium, using an energy of 75 keV (average among the most common energies for this radioisotope), the behavior presented in Fig. 7 was obtained. There, and in the following graphs, the red line indicates the maximum permissible dose for occupationally exposed workers, which is used as a reference to know the distances at which it is considered safe to be. It can be seen that from a distance of 12.8 cm the dose received does not exceed the “safe” dose, both for the case that does not have a lead wall and for any lead wall thickness. As the distance increases, the received dose becomes smaller, as with the increase of the thickness of the lead wall. It is also appreciated that is not necessary to use a lead wall to attenuate the radiation, since the intercept with the line that indicates the safe dose is before the distance at which the lead shield is located. The radiation attenuation observed both before and after the lead wall is a consequence of absorption in air. As can be seen in the calculation, this absorption is insignificant compared to that which takes place inside the protective wall, given its much higher atomic number and density. With the increase of the wall thickness, the radiation absorption in it improves for the benefit of achieving better protection.

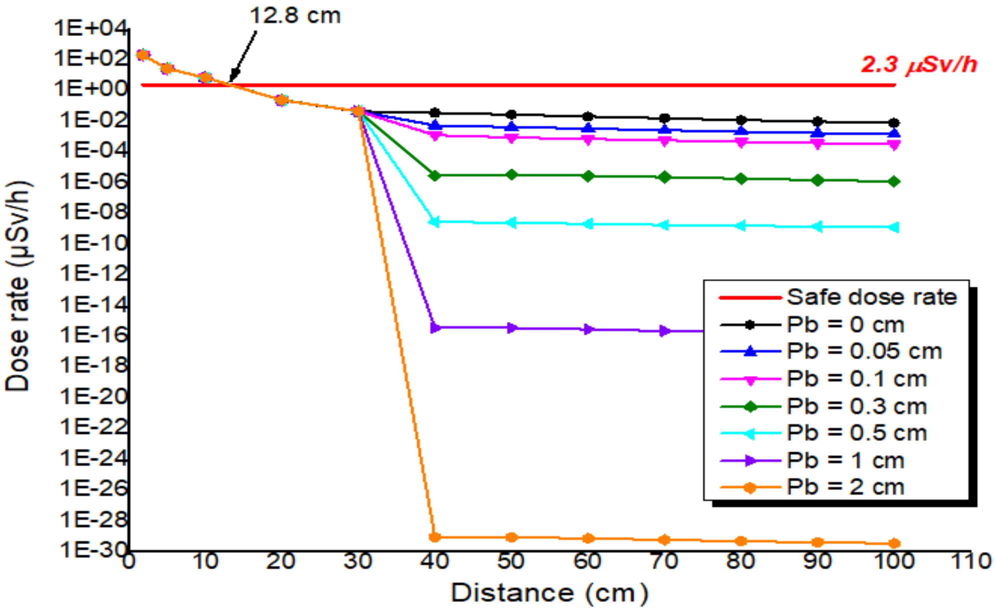

Fig. 7: Distance dependence of the Dose Rate for different lead wall thicknesses in the SPECT configuration with the ^{201}Tl isotope.

By using Technetium as a SPECT source, taking its energy as 140.5 keV, the graph shown in Figure 8 was obtained. In this case, where the energy is higher, the smallest safe distance is 20.1 cm. From there, for any of the lead thickness, the dose does not exceed 2.3 μSv/h. In this case, the location of the lead protection is not necessary either since the intercept is before the position in which this wall is located.

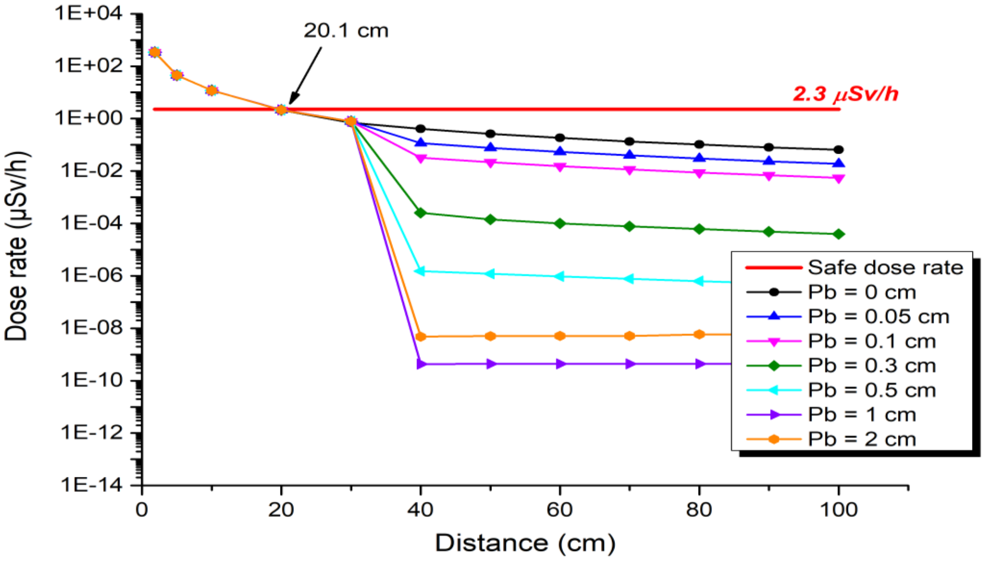

Fig. 8: Distance dependence of the Dose Rate for different lead wall thicknesses in the SPECT configuration with the ^{99m}Tc isotope.

For the Iodine source in SPECT configuration, with energy of 364 keV, was obtained the following graph (see Fig. 9). The safe distance is 35.3 cm for no shield protection and decreases to 30.4 cm when is used 2 cm of lead. In this case, the lead wall is very important since the intercept with the safe dose line is obtained in the vicinity of its position. This indicates that the attenuation of lead to radiation is essential to minimize the safe distance.

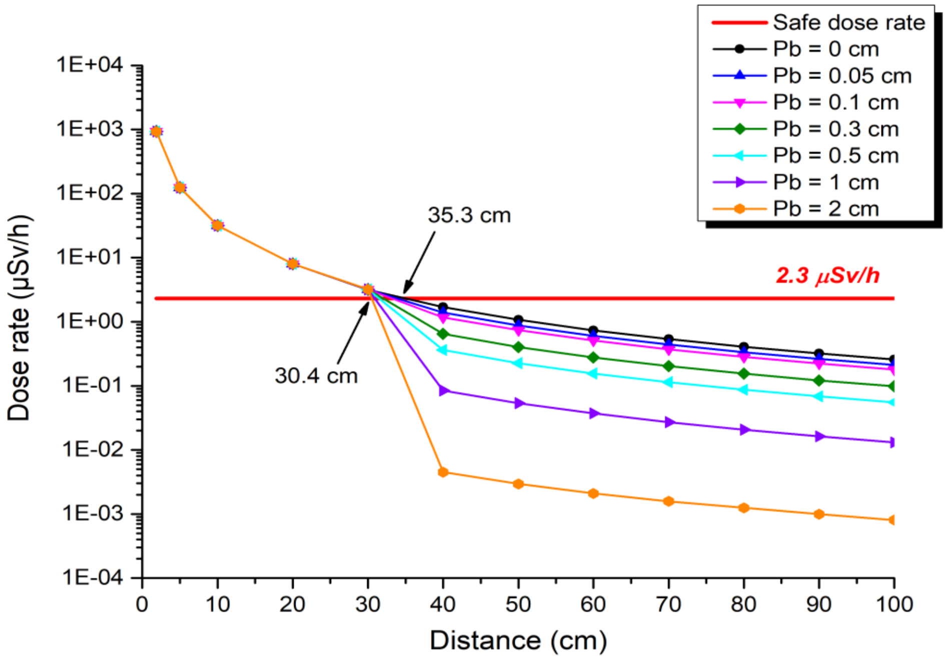

Fig. 9: Distance dependence of the Dose Rate for different lead wall thicknesses in the SPECT configuration with the ^{131}I isotope.

CT

Was analyzed the case of a Tungsten tube, with a certain spectrum of energies. As in the analysis of the SPECT, was varied the lead wall thickness placed at 33 cm from the source. From this simulation was obtained the graph presented in Figure 10. It can be observed that for the CT the protection of lead is essential. As the wall thickness decreases the safe distance becomes greater. In the case where there is no wall, the distance becomes 3550 cm. For the case in which the protection wall is 0.05 cm, safe distance is obtained at 1348 cm. For the largest value of lead wall thickness (2 cm), safe distance is 32.1 cm.

As can be deduced from the results, although in the SPECT measurements the lead wall does not constitute an important protection, since without its help it can be guaranteed that the safe distance for the work of the personnel is small enough and the dose is not harmful, for CT is very important. That is why in the case of working with CT it is recommended to take additional protection measures.

For workers, measures must be taken such as the implementation of individual cards or individual files that allow them to see the level of exposure to which they are being subjected and not exceed the limits. Protection means such as leaded aprons, leaded gloves and collar, and special leaded glasses can also be used.

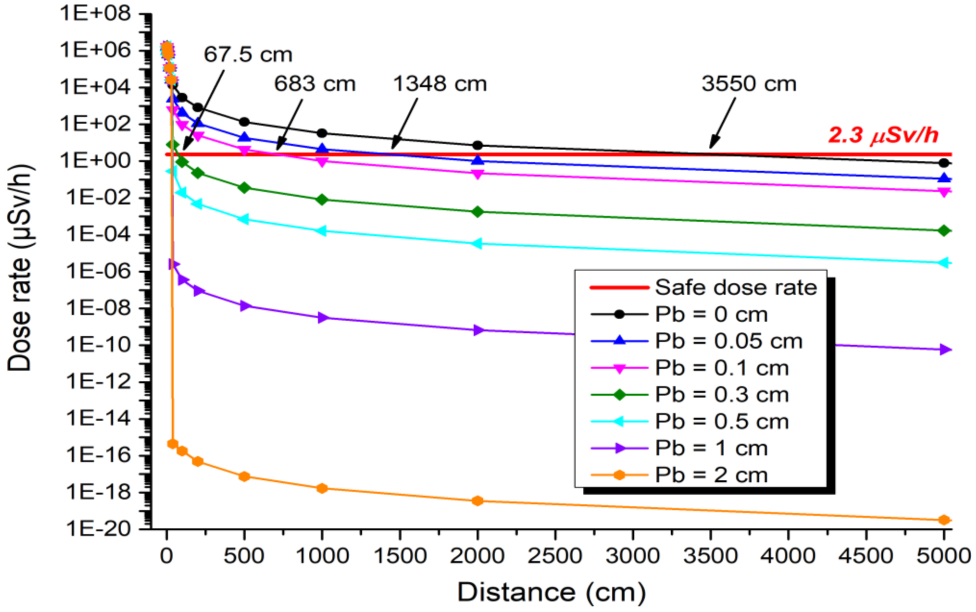

Fig. 10: Distance dependence of the Dose Rate for different lead wall thicknesses in the CT configuration.

Conclusion

Using the based-on Monte Carlo code system MCNPX, it was possible to simulate the dose rate distribution in a preclinical SPECT-CT image scanner. For the detailed study of the task, a Tungsten Roentgen tube and three different gamma radioisotopes were used. The thickness of a lead wall was also varied in the range of 0 cm to 2 cm. The dose rate for each geometric arrangement was measured at different distances from the irradiated target and compared with the dose internationally recognized as safe (2.3 μSv/h).

For SPECT, was obtained a direct relationship between the safe distance and the energy of the radioisotope, as one increases the other increases too. It was estimated that the safe distance for exposed workers with no shield protection varies between 12.8 cm (^{201}Tl) and 35.3 cm (^{131}I).

For CT, the safe distance obtained without shield was 3550 cm. With this result becomes necessary to place a lead wall thick enough to attenuate radiation and protect every person in the room, except for the patient. With a 2 cm thick this distance drops to 32.1 cm, but even with a 0.3 cm thick this distance decreases to 67.5 cm, which is a fairly affordable value. However, it is always advisable to take additional protective measures.

References

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