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

Radiation from ionizing sources are used for various groundbreaking medical procedures, nonetheless, it presents a risk and a threat to the occupational personnel´s health. Because of this, their safety in these medical settings is crucial. To prevent and minimize the consequences, various methods of protection against ionizing radiation are used. This work showcases one of those methods for the case of a SPECT/CT preclinical micro scanner, by utilizing MCNPX code systems based on Monte Carlo methods it's possible to determine at which distance and, if needed, how thick a lead wall in between the personnel and the source must be so that the occupational personnel is in a safe dose rate working environment.

Introduction

Nuclear medicine is a medical specialty that uses a trace amount of radioactive substances for the diagnosis and treatment of many health conditions such as cancer.

The safety of the medical staff follows strict rules and are trained to ensure their safety, in addition to those rules, the design and construction of the infrastructure of the facilities are carefully thought out to ensure the protection of the personnel from the ionizing radiation, taking into account the 3 principles for radiation protection TDS (time, distance and shielding).

During the design and development, commissioning tests are carried out to ensure that the equipment is as harmless to human health as possible, for this, mathematical modeling of radiation transfer is used.

The present work aims to evaluate the proper shielding and distance that must be held by the facility and its medical staff while performing SPECT/CT diagnosis with various radioactive sources by utilizing Monte Carlo method code system MCNPX to simulate the real-life procedures.

Materials and Methods

SPECT/CT tomography

CT

Computed Tomography is an imaging technique that uses X-rays to create a cross-sectional image of the body’s bones, blood vessels and soft tissues in search for any anomalies in these parts.

It’s equipped with a motorized X-ray source and detectors on the opposite side of the source that revolve around the opened circular structure by the name of Gantry.

The patient is placed on a motorized bed that slowly moves through the Gantry while the X-ray tube and detectors spin around the patient, creating a 3D image by complex mathematical algorithms performed by the CT computer’s software, as seen in *Figure 1*, therefore, providing a much more detailed and telling image than other techniques such as MRI.

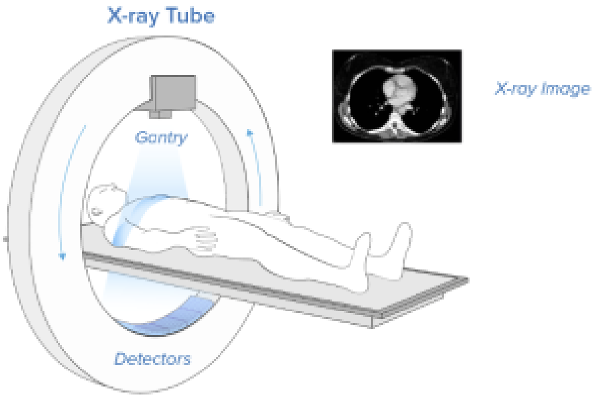


Figure 1. CT procedure, parts and image.

The X-ray tube is considered the heart of the CT, placed inside the Gantry, it houses a cathode and an anode that are separated in a vacuum. When a high voltage is applied to the cathode, which is negatively charged, it emits a stream of electrons which are then accelerated towards the anode by the electric field created by the voltage difference. Once the electrons collide with the anode, X-rays are produced.

X-rays being high-energy photons that can penetrate through solid objects, including the human body, the detectors are responsible for capturing the X-rays that pass through the examined body and converting them into electrical signals to the computer which turns these signals into 2D images.

The images are stacked by the computer one on top of the other from different angles to create 3D images.

SPECT

Single photon emission computed tomography (SPECT) is a radionuclide imaging technique.

The procedure consists of utilizing radiopharmaceuticals that emit at least one gamma ray when they decay and, therefore, can be used as a tracer introduced through IV that travels to a specific organ/s for its study.

Since gamma rays are normally emitted equally in every direction, it is necessary to use a collimator in front of the detector that allows only gamma rays emitted in the direction of the detector to be registered, as portrayed in *Figure 2*.

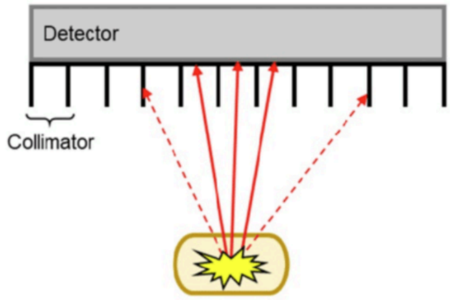
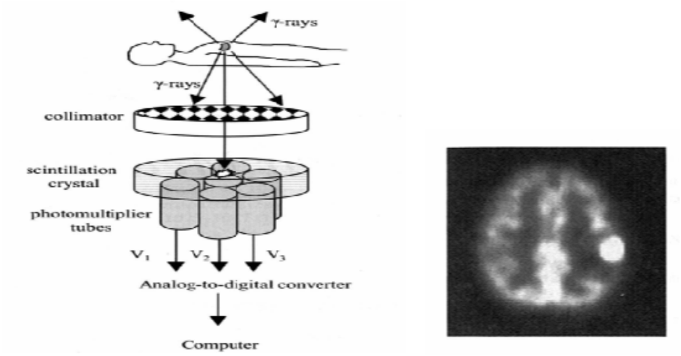


Figure 2. Linear SPECT detector with collimators.

Mathematical methods are used to trace the emitted gamma rays back in the direction that they were emitted in order to produce the image, a representation of this process and the obtained image can be seen in *Figure 3*.



(a) Basic principles (b) Captured image

Figure 3. (a)Basis of SPECT (b)Captured SPECT image.

The SPECT machines combine an array of gamma cameras that rotate around the patient on a gantry as seen in *Figure 4*, providing spatial information on the distribution of the radionuclide within tissues. The images obtained are then reconstructed into 3D images.

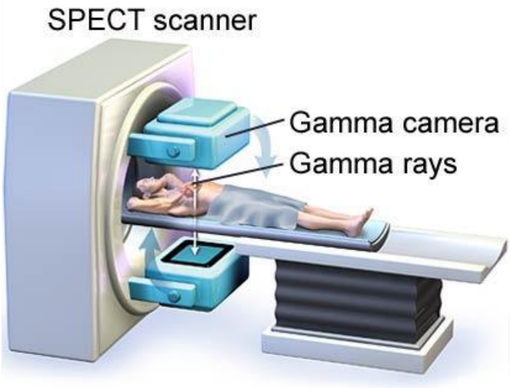


Figure 4. SPECT machine and parts.

SPECT-CT

Single photon emission computed tomography-computed tomography (SPECT-CT) is a hybrid technique that directly fuses anatomical and functional information from the CT and SPECT components respectively, shown in *Figure 5*, working in unaccent where CT images reveal the localization of radionuclides and provide a means for attenuation correction of SPECT emission images.

The SPECT CT combines a low-power X-ray tube with separate gamma and X-ray detectors mounted on the same slip ring gantry that can rotate 360 degrees, providing spatial data for generating sharp, detailed 3D images, allowing for easy visualization of abnormalities, assisting in accurate result interpretation, and taking only 30 minutes to complete the examination.

Images from SPECT and CT are combined to form a new 3D image known as a fused image, which shows the location of abnormal accumulation as a bright area of radioactive tracers (CT typically shows black and white spots), allowing the nuclear radiologist to identify small lesions, cancers, tumors, or abnormal organ function.

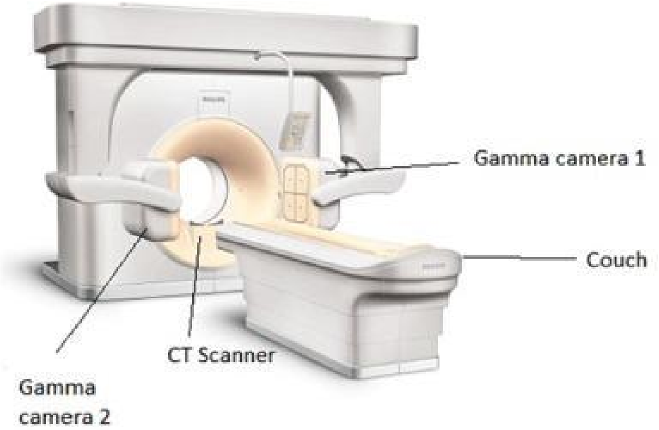


Figure 5. SPECT-CT machine and parts.

Sources used in SPECT/CT

The sources used for SPECT procedures are dependent on the part of the body that will be examined, and it's also based on the levels of energy of said radioisotope used, from the applied radiopharmaceutical it will also change the collimator used.

The SPECT is equipped with collimators adequate for the specific radioisotope in use, such as low energy gamma emitters, high resolution parallel hole collimators for ^{99m}Tc, or medium energy gamma emitters collimators for ^{67}Ga, ^{111}In, ^{81}Kr or ^{131}I.

The radioisotopes used in SPECT are selected based on a combination of physical, chemical, and biological properties that make them ideal for diagnostic imaging. Based on these characteristics, the most commonly used radioisotopes for SPECT procedures are enlisted in *Table 1* with some of their key properties.

Radioisotope	Half-Life	Energy (keV)
^{177}Lu	6.7 days	113 208
^{67}Cu	2.58 days	185
^{99m}Tc	6.02 hours	141
^{123}I	13.22 hours	159
^{131}I	8.02 days	364
^{201}Tl	73 hours	72
^{67}Ga	78	93 185
^{111}In	2.8 hours	171 245
^{81m}Kr	14.4 seconds	190
^{133}Xe	5.3 days	81

Table 1. Most used radionuclides for SPECT/CT procedures, their half-life and energy levels expressed in KeV.

The source of X-ray radiation in CT is the Roentgen or X-ray tube shown in *Figure 6*, where the anode converts the energy of incident electrons into X-rays, this makes the material of which the anode is made responsible for the energy of the emitted X-ray. Most X-ray tube anodes are made of tungsten (W), tubes with anodes made of silver (Ag), rhodium (Rh) or gold (Au) are amongst the most commonly used, nonetheless, the high atomic number of tungsten gives more efficient bremsstrahlung production compared to lower atomic number target materials, as shown in *Figure 7*.

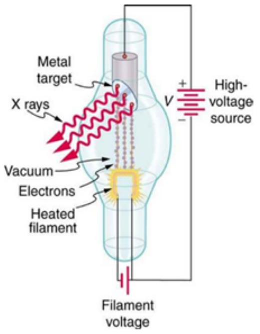


Figure 6. X-ray tube and its parts.

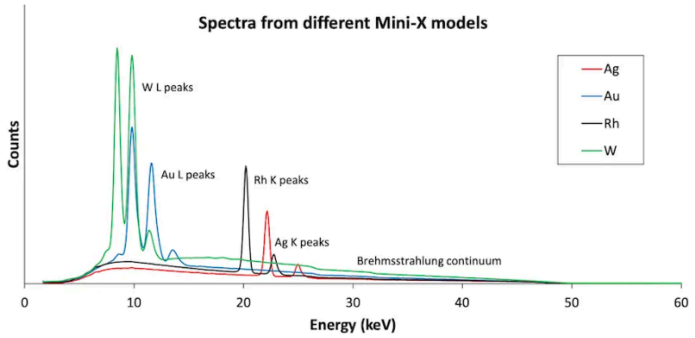


Figure 7. Ag, Au, Rh and W anode spectra, showing the dependency of the energy of the X-ray with the material of the anode.

Dose safe limits

The radiation absorbed dose delivered to the patient from the use of CT in SPECT/CT is based on CT Dose Index (CTDI) which is able to represent an index of radiation dose to a standard phantom.

However, If the dose distribution from the centre to the edge of the phantom as well as the pitch used in the scan is considered, a term called CTDIvol can be used to represent the dose index to the volume of the phantom. The CTDIvol associates a single CT scan covering one SPECT bed position.

The effective dose and CTDIvol values from typical SPECT-CT scans to the chest and abdomen have been calculated, and they are 4 mSv and 8 mGy, respectively. The value to the head and neck are 4 mSv and 10–20 mGy, respectively. These doses are for one SPECT bed position, relating to a 39 cm CT scan length.

Doses can be scaled linearly with the actual scan effective mA for the patient study. These measures ensure an adequate planning view with the lowest dose to the patient, which is about the same as for a single view of the chest X-ray.

The International Atomic Energy Agency (IAEA) in its new basic safety standards has changed the annual eye lens dose limit for radiation workers from 15 mSv to 20 mSv averaged over five years but not to exceed 50 mSv in a single year, other dose limits are dependent on the classification of the person and specific body parts, this is shown in *table 2.*

	Occupational	**Public**	**16-18 year old students**
Effective dose	50 mSv / year, 20 mSv averaged over 5 years	1 mSv / year	6 mSv / year
Equivalent dose in the lens	20 mSv	15 mSv / year	12 mSv / year
Equivalent dose in the skin	500 mSv / year	50 mSv / year	60 mSv / year
Equivalent dose in extremities	500 mSv / year		60 mSv / year

Table 2. Permissible dose limit for occupationally exposed personnel, the public and students.

Interaction of photons with matter

A photon is a conjunction of electromagnetic energy that possesses no mass nor charge that travel at the speed of light. Even though gamma rays and X-rays are both forms of electromagnetic radiation. They differ only in their source. A gamma ray emanates from the nucleus of a radioactive atom. An X-ray emanates from outside the nucleus of a radioactive atom, or from an electron as it changes direction when passing an atomic nucleus.

Photons interact differently in matter than charged particles because photons have no electrical charge. Because it is not charged, a photon does not interact by coulombic force, but rather only by interaction with an electron. The interaction of photons with electrons is completely probabilistic. And depends on the photon's energy and the atomic number and density of the material.

The three most common forms of interaction are the photoelectric effect, Compton scattering and pair production. The interactions and their photon energy range are shown in *Figure 8.*

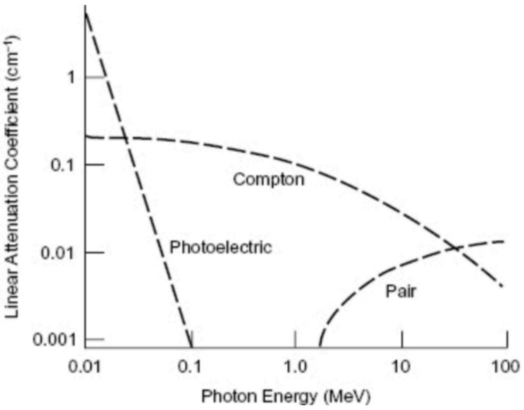


Figure 8. Probability of interaction versus photon energy for the photoelectric effect, Compton scattering, and pair production.

Photoelectric effect

At energy levels from several tens to one hundred kiloelectron volts, the predominant mode of photon interaction is the photoelectric effect, here the photon is completely absorbed by an inner shell electron of an atom that makes the photon completely disappear and the shells of the atom eject a photoelectron, which leads to fluorescence radiation or X-ray; this process is shown in *Figure 9*.

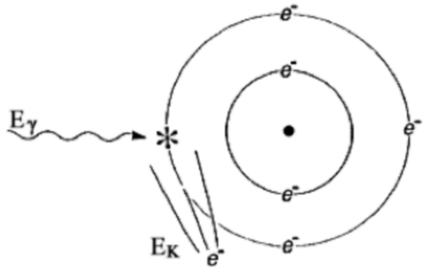


Figure 9. Photoelectric Effect, The photon is completely absorbed. Its energy E_γ liberates an electron bound with energy E_B, and provides it with kinetic energy E_K.

Photoelectric effect interactions are desirable in shields for photons since the photons are completely absorbed, on the other hand, they are not desirable from the standpoint of absorbed dose to human tissue.

Compton Scattering

The Compton Scattering is more prevalent at energy levels in the range of 100 keV to 10 Mev. In this interaction, the photon is deflected through an angle different from its original direction; by this change of direction and impact, it transfers energy to a loosely bound outer shell electron of an atom, this electron is known a Compton or recoil electron. This is shown in *Figure 10.*

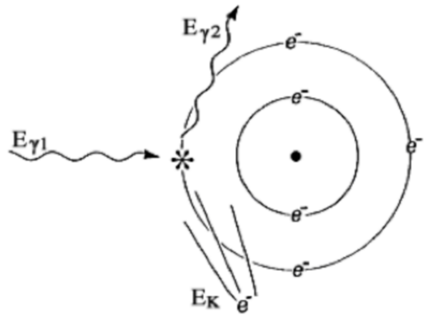


Figure 10. Compton Scattering, An incident photon with energy $E_{\gamma 1}$ liberates an orbiting electron, yielding a recoil electron with kinetic energy E_K and a lower energy scattered photon with energy $E_{\gamma 2}$.

Although it is most prevalent at the energy levels mentioned above, it occurs at all photon energy levels and in all material almost independent of the atomic number which makes it the most probable type of interaction, the energy transferred dependent only on the angle on which the recoil electron is deflected and the initial energy of the photon.

Pair Production

If matter enters with an energy higher than 1.022 MeV it can interact in a way called pair production, this is because the electron and positron each have an energy equivalence of 511 keV, the incoming photon must have an energy of at least 1,022 keV for pair production to take place.

In pair production, a photon interacts with the electric field of the nucleus of an atom; here, the photon completely disappears while an electron and a positron are produced as it's shown in *Image 11*. Any additional photon energy above 1,022 keV is given to the positron and the electron as kinetic energy. The electron and positron will give up their kinetic energy via ionization or excitation.

This interaction is most likely to occur with relatively high photon energies(>10MeV) and high atomic number materials (bigger nuclei of the atom).

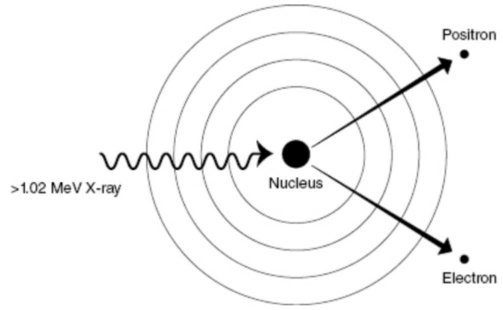


Figure 11. Pair Production, An incident photon with energy equal or greater than 1.022 MeV can generate a positron-electron pair. The positron and electron have rest masses of 0.511 MeV and share the excess kinetic energy.

Monte Carlo method

In general, the Monte Carlo method provides a numerical solution to a problem that can be described as an evolution of objects interacting with other objects based on their relationships processing them randomly and repeatedly until finally it results into estimated means. Interactions between particles such as photons, electrons, neutrons, nuclei and diverse materials can be simulated and estimated by this method.

Widely used in medical physics for modeling the nature of the interaction of the various charged particles present in these procedures, and thus explaining, from a microscopic view, a macroscopic system.

Monte Carlo schemes can be developed, generating trajectories and coating histories of many tablets very rapidly in a simple computer simulation. The coating statistics of those tablets then combine all the simulated sources of variability. While this method is very attractive once the relevant variability source statistics have been acquired, acquiring them must be done for each process change to ensure accurate results.

MCNPX for modeling radiation transport in matter

Monte Carlo N-Particles eXtended (MCNPX) is a general-purpose Monte Carlo radiation transport code with three-dimensional geometry and continuous energy transport of 34 particles and light ions. It contains flexible source and tally options, interactive graphics, and support for both sequential and multiprocessing computer platforms. Serving as an extremely useful tool for shielding or energy deposition calculations.

It's extensively used in radiation transport in matter by singling each particle and following its trajectory through complex geometries while simultaneously taking into factor the specific conditions at every interaction point the particle encounters, resulting in a detailed representation of radiation transport.

VisedX-22S for visualization of the simulated environment

VisedX is a visual editor for MCNPX Monte Carlo codes that enables the users to visualize the simulated setups as well as the particles and their behavior with matter of the MCNPX codes by creating 2D and 3D views of those setups, facilitating their understanding and, if needed, modifications.

OriginPro for graphic representation of MCNPX results

OriginPro is a data analysis and graphing software program, equipped with various tools to comprehend the processed data.

Results

The setup used for SPECT and CT procedure is shown in *Figure 12.* To evaluate the proper distance and shielding from the radioactive source required in the facilities so that the clinical staff is receiving equal or less dose rate than the Safe Dose Rate Limit (2.3 μSv/h) positioning the lead wall 33 cm from the ionizing source.

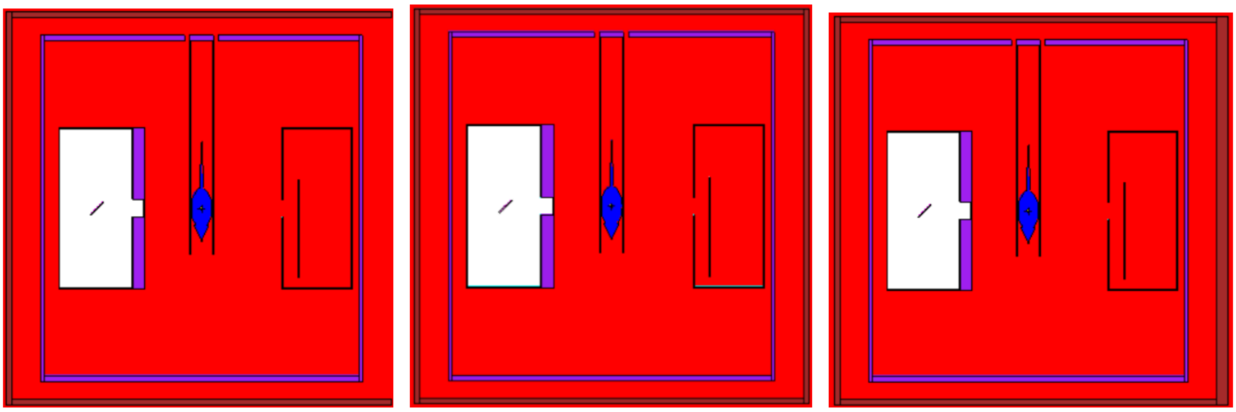

(a) (b) (c)

Figure 12. 2D model of SPECT/CT scanner with lead wall thickness (a) 0 cm, (b) 1 cm and (c) 2 cm.

The different lead wall thicknesses evaluated for CT procedures were 0 cm, 0.05 cm, 0.1 cm, 0.3 cm, 0.5 cm, 1 cm and 2 cm. With an X-ray source with a W anode operating at a potential difference of 120 kV and a current of 350 mkA.

The different lead wall thicknesses evaluated for SPECT procedures were 0 cm, 0.05 cm, 0.1 cm, 0.3 cm, 0.5 cm and 1 cm.

SPECT

The visualization of the particles and tracks from ^{99m}Tc source in the SPECT setup can be viewed in *Figure 13.* The ^{99m}Tc source, presenting an energy of 140.5 keV and a radioactive activity of 10 MBq.

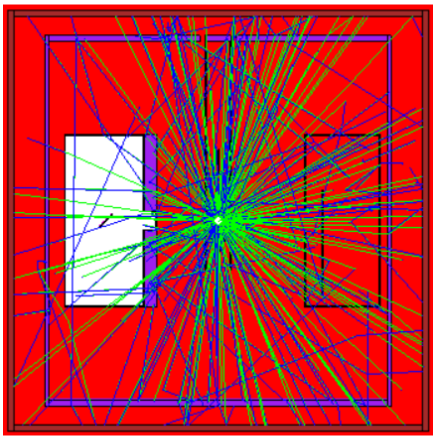


Figure 13. Track display, air (red), photons (green) and secondary electrons (blue), for SPECT/CT system with ^{99m}Tc source.

After executing the mathematical modelling of the described setup using MCNPX, we obtain the dependence of the dose rate on the distance for each value of Pb wall thickness. This behavior is presented in *Figure 14*, observing, as expected, a monotonically decreasing dependence in all cases. The results show that the safe dose rate limit is reached at a distance of 22.6 cm, this is, before the Pb wall, indicating that this protective wall is not necessary to guarantee the protection of occupationally exposed personnel.

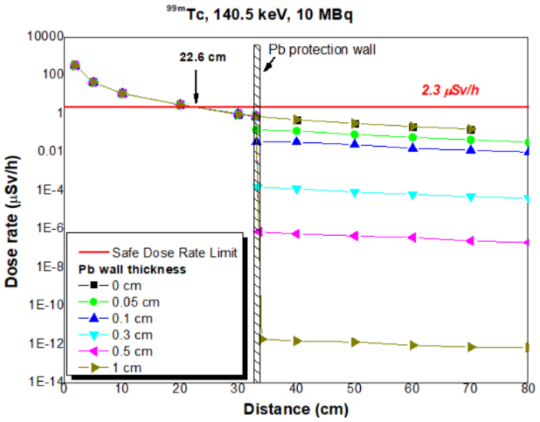


Figure 14. Distance dependence of dose rate for different lead wall thickness for SPECT/CT system with ^{99m}Tc source.

As well as the ^{99m}Tc source, the same procedure and calculation were done to the ^{131}I, with an energy of 364 keV and at 10 MBq of radioactive activity. The particle display is shown in *Figure 15.*

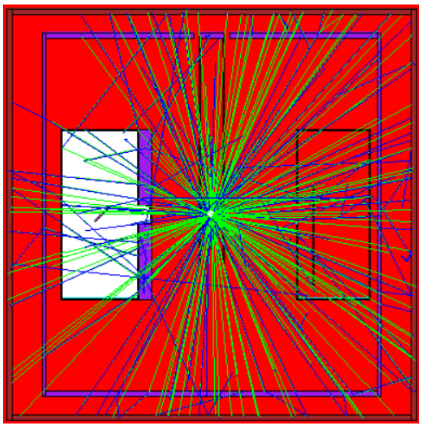
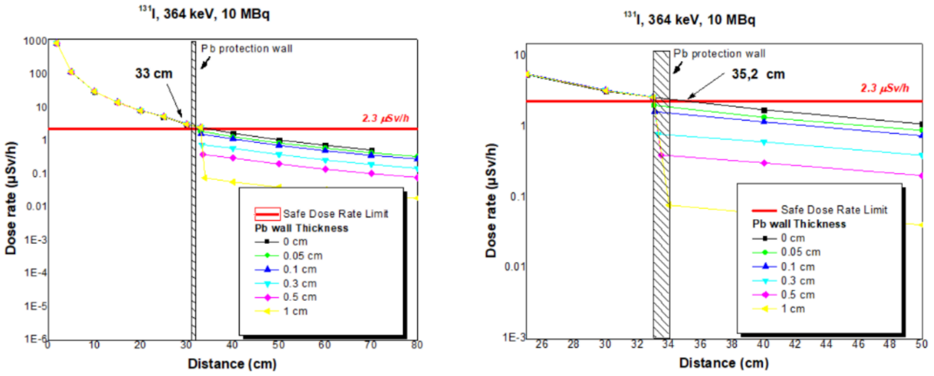


Figure 15. Track display, air (red), photons (green) and secondary electrons (blue), for SPECT/CT system with ^{131}I source.

Once the calculation results are graphed, shown in *Figure 16*, it can be seen that the dose rate is below the safe dose rate limit in all cases where the lead wall is present at 33 cm from the source, the same does not occur when there's no lead wall in between, in this, case the safe dose rate limit is only reached at 35.2 cm from the source.



(a) (b)

Figure 16. Distance dependence of dose rate for different lead wall thickness for SPECT/CT system with ^{131}I source. (a) Showcasing the distance where dose rate limit is reached with lead wall as protection (b) Close up of (a) showcasing the distance where dose rate limit is reached with no lead wall protection.

CT

For the CT configuration, the X-ray tube is the source, however, the X-ray beam is being directed towards the patient, in this procedure a rat, which is located in the center of the setup, seen in *Figure 17*. The evaluated tallied distance ranged from 1.85 cm to 8,000 cm.

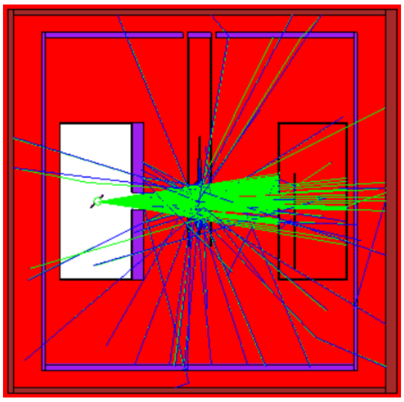
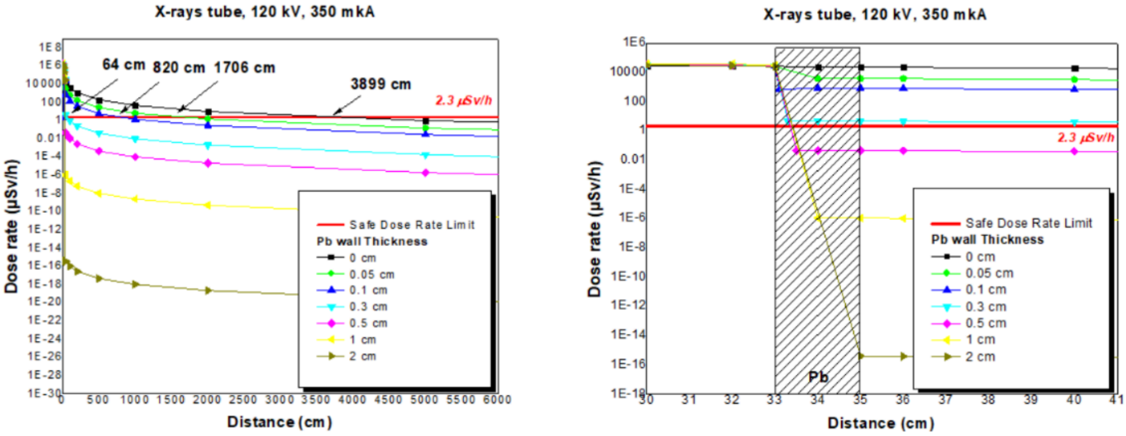


Figure 17. Track display, air (red), photons (green) and secondary electrons (blue), for CT system with X-ray source with voltage of 120 kV and current of 350 mkA.

Similarly to SPECT configuration, for CT scan it was evaluated the shielding and distance where the dose rate limit is reached. This is seen in *Figure 18*.



(a) (b)

Figure 18. Distance dependence of dose rate for different lead wall thickness for CT system with X-ray tube. (a) Distance where dose rate limit is reached at different lead wall thickness (b) Close up of (a) in the location of lead wall.

As well as the radioisotopic sources of the SPECT, the dependence of the dose rate with the distance for each value of Pb wall thickness in CT is monotonically decreasing, as seen in *Figure 18*. However, the inferior attenuations and the safe dose rate values are reached at much longer distances than in SPECT, reaching the safe dose rate limit at nearly 4 meters at the absence of the Pb wall, at 1.7 meters for 0.05 cm of thickness 0.82 meters for 0.1 cm of thickness and 64 cm for 0.3 cm thickness.

The only thicknesses where the dose rate limit is reached at the place of the Pb wall (33 cm) are from 0.5 cm and above, as it's portrayed seen in *Figure 18 (b)*. By this, the importance of the Pb wall can be clearly stated for this particular system.

Conclusions

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.

With the obtained results, it was possible to determine the minimum safe distances and lead wall protection required for various nuclides used in SPECT diagnostics as well as for W anode X-rays in CT scans.

When using ^{99m}Tc as the radionuclide source for SPECT diagnostics, it can be seen that for this setup the lead wall is not necessary to be in the dose rate limit, this is reached at 22.6 cm from the source.

As for the source is ^{131}I, with no lead wall the rate dose limit is reached at 35.2 cm this means that is not viable for occupational personnel since they are located at 33 cm from the source. When the lead wall is present at any thickness the dose rate gets below the limit as soon as it reaches the wall. This indicates that the thinnest lead wall is enough to keep the personnel safe from major dose rate.

The same analysis was made for CT, based on the obtained results, it is necessary to have no less than a 0.5 cm thick Pb wall to ensure that the occupational personnel is under the safe dose rate limit in this setting.

Taking all into consideration, for this preclinical SPECT/CT system, to ensure that the occupational personnel is receiving at most the safe dose rate limit independently of the evaluated radioisotopic source for SPECT and or CT procedure, the Pb wall must not be lower than 0.5 cm. Even so, it is always advisable to take additional protective measures against dose rates.

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