JOINT INSTITUTE FOR NUCLEAR RESEARCH

Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE INTEREST PROGRAMME

Monte Carlo simulation of radiation-matter interactions for shielding evaluation in preclinical SPECT/CT scanner.

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Abstract

Radiation sources can cause hazards when being used without any protection in medical physics, so the aim of this work is to assure that the scanner of the CT/SPECT is well shielded and the radiations interact with the matter within the safe limit. This study has been carried out using the MCNPX code system that allowed to determine the distribution with distance of the dose rate.

For the CT array we used the X-rays with a W anode Roentgen tube, and for SPECT two of the most widely employed in medicine radionuclides (^{99m}Tc and ^{131}I) were used. **The objective of this work is to know and determine the minimum safe distances for personnel occupationally exposed to radiation from some of the radiation sources used in preclinical SPECT/CT scanners, and to assess how the use of a lead wall with different thicknesses contributes to changing safe distance values.**

Table of Contents

1. Introduction

Nuclear medicine uses radiation to give information about the functioning of a person's specific organs, or to treat disease as inflammation, cyst, tumor, etc. The most common radioisotope used in diagnosis is technetium-99m.

For the increase in nuclear medicine applications, it is crucial to maintain protection against ionizing radiation at an adequate level so as not to cause harm to people working in facilities or to patients. Due to the negative effects of a high dose of radiation when being exposed to it, we find it is essential to know the dose exposure for workers and other personnel, then we guarantee that the operation of a certain installation of a similar nature is safe for the personnel who is responsible to operate it.

Our report analyzes and studies the role and importance of radiation shielding in a preclinical SPECT/CT scanner. For this we will use the mathematical simulation based on the Monte Carlo method of radiation transport in matter, which is most suitable to run simulations in near-real conditions. The results would allow the necessary measures to be taken.

Also, the percentages of attenuation for both SPECT and CT are discussed by comparing and analyzing our graphs to the measurements given by ICRP which are used as a guideline for assessments.

2. The basic principle and operation of computed tomography (CT):

The Goal: create cross sectional images with the help of computer processing.

1- Inside a vacuum tube, electrons produced by a heated cathode toward a rotating anode, which converts electron energy into X-rays and dissipates heat.
2- The X-rays pass through collimators creating a beam that is aimed at the desired area.
3- The patient is placed in a tubular gantry surrounded by a ring of X-ray detectors in the opposite to the X-ray tube
4- When the rotating X-ray beam enters the body and here, we have tissues of different density, the absorption varies with undergoes attenuation (decrease in energy and number of photons), which is recorded by the X-ray detectors upon its exit from the body.
5- The detectors convert the exiting beam into amplified electrical pulses that vary in intensity according to the residual beam strength. The acquired data is sent to a computer that analyzes the location and density information and generates axial, cross-sectional images of internal structures of the body.

Figure 1: is a simple schematic representation of a CT arrangement. Axial slice through the patient is swept out by a narrow (pencil-width) X-ray beam as linked X-ray tube–detector apparatus scans across a patient in linear translation. Translations are repeated at many angles. The thickness of a narrow beam is equivalent to slice thickness.

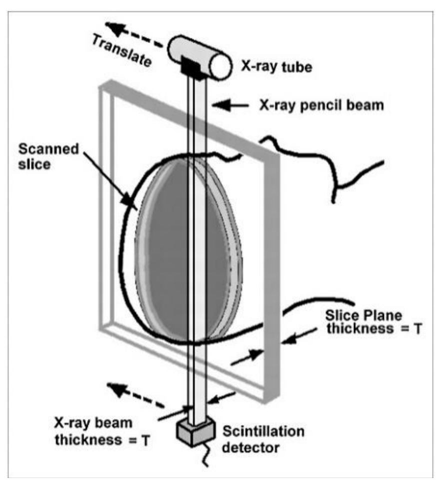


Figure 1. General CT arrangement for scanning the human head.

As the conventional X-rays uses a fixed tubes that sends the X-rays in one direction that limits its ability to visualize low contrast tissues and structures with acceptable levels of patient radiation exposure, but in the CT scanner each time the X-ray tube and detector make one complete rotation (see Figure 2), an image or slice is acquired. Image slices can be displayed individually on 2D or stacked together to generate a 3D image that can reveal the abnormal structure.

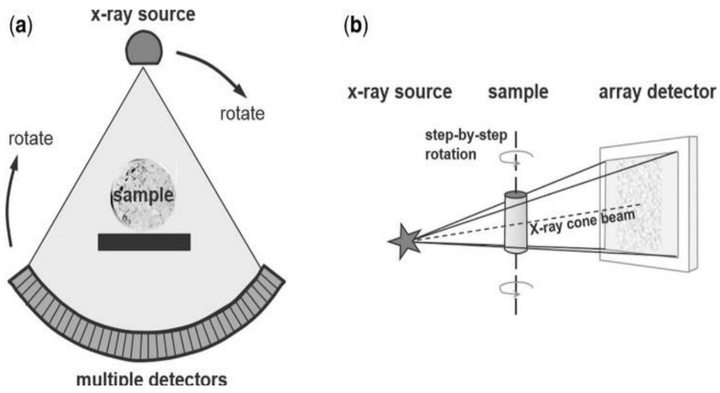


Figure 2. Two different configurations used in a modern third-generation CT system. (a) rotating the X-ray source and detector array, and (b) rotating only the sample under study.

2.1 CT system main components and their functions:

The system consists of scanning moving gantry which a frame containing X-ray tube, collimator, computer system, console panel and a viewing console. Figure 3 shows the basic components of a modern CT system. Most CT Scanning systems include a laser printer for transferring CT images to film.

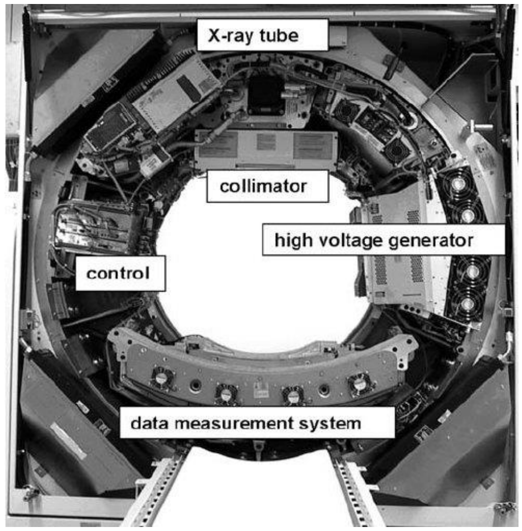


Figure 3. Basic system components of a modern third-generation CT system.

The three basic segments of image processing are Data Acquisition, Image Reconstruction, and Image Display.

The imaging system is made up of two main components located within the simulator which are:

1) CT Scanner: A computed tomography scanner is used to create cross-slices of different objects and CT scanners are composed of three essential elements: an X-ray tube, a gantry with a ring of X-ray sensitive detectors, and a computer.

2) Laser System

Scanner Gantry: includes the X-ray tube, the detector array, the high-voltage generator, the patient support couch, and the mechanical support for each. The scanner acquires the image data that will be constructed by the virtual simulation.

A) X-ray Tube.

B) Scanner Bore: the use of wide-bore scanner gives low contrast resolution and increases image noise compared standard scanner.

C) High-speed Rotor are used in most for the best heat dissipation. Experience has shown that X-ray tube failure is a principal cause of CT imaging system malfunction.

D) Detector Array: Multi-slice helical CT imaging systems have multiple detectors in an array up to tens of thousands.

E) Scanner Couch:

Laser System

There are three types of lasers used:

1- Internal laser
2- Wall-mounted laser (incapable of movement)
3- Overhead saggital laser (capable of lateral movement)

3. The basic principle and operation of Single photon emission computed tomography (SPECT)

The principle of SPECT working is based on the radioisotopes that emit single photons, unlike other types of scanners that use, for example, positron-emitting radioisotopes, as is the case with the PET scanner. The most used radioisotope in SPECT tomography in medicine is technetium-99m (photon energy 140.5 keV), (see the decay scheme of ^{99m}Tc in figure 4).

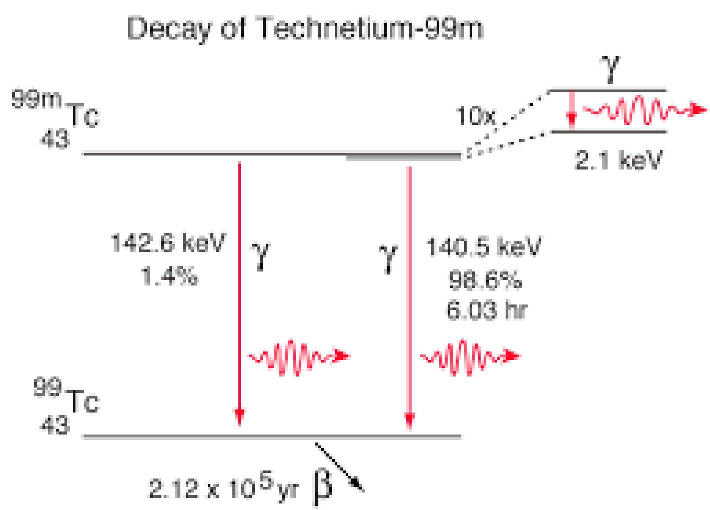


Figure 4. Diagram representation of the ^{99m}Tc decay.

The SPECT system comprises of a conventional gamma camera mounted on a special gantry and connected to a computer system.

A series of planar images are collected, while the camera is rotated through either 180° or 360°, around the patient.

These planar images are called projection images and are used to create transaxial slice images by filtered back projection of the data into a transaxial plane. each projection image consists of counts in each pixel: Each pixel counts are corrected for attenuation Image quality depends on the integrity of the counts in each pixel in each view. Apart from the usual problems of uniformity, linearity and count rate capability that exist with the gamma camera.

3.1 SPECT system main components and their functions:

The main components of a SPECT system.

(a) gamma camera
(b) patient couch, it is made from a special material to minimize attenuation. It should be possible to align the long axis of the bed with the axis of rotation of the camera.
(c) gantry controlled by microprocessor interfaced to main computer.
(d) rotation controller
(e) emergency stop and other patient safety devices
(f) position read-out device

- Transmission tomography: measuring the transmittance of object: transparency Source is located outside of the object
- Emission tomography: measurement of source distribution inside of object Source is located inside of the object

The following image, **figure 5**, shows as a summary, a general scheme of the working principle of a SPECT system.

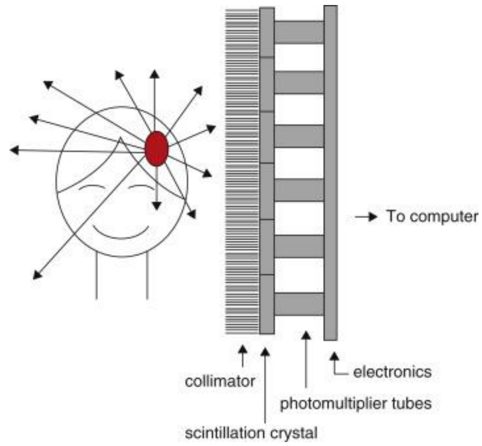


Figure 5. General scheme of the SPECT tomography working principle.

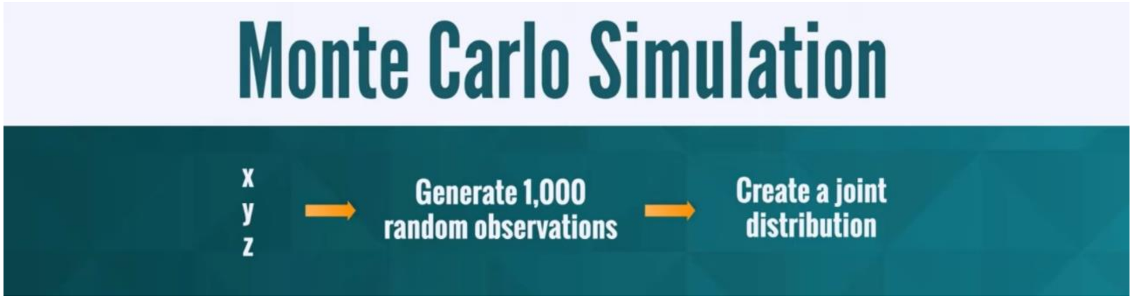
4. Monte Carlo method

What is the Monte Carlo method? Monte Carlo is a type of computational algorithm that uses repeated random sampling to obtain the likelihood of a range of results of occurring, also it is a mathematical technique, which is used to estimate the possible outcomes of an uncertain event. with being a way of solving a deterministic problem by a stochastic approach using random numbers as it is particularly useful for complex problems that cannot be modeled by computer codes that use deterministic methods.

How does Monte Carlo Simulation work?

Monte Carlo Simulation predicts a set of outcomes based on an estimated range of values versus a set of fixed input values. As it builds a model of possible results by a probability distribution, such as normal distribution, for any variable that has uncertainty. It recalculates the results over and over, each time using a different set of random numbers between the minimum and maximum values.

How to use Monte Carlo methods?



Regardless the tool used, Monte Carlo techniques involves three basic steps:

1. Set up the predictive model, identifying both the dependent variable to be predicted and the independent variables.

2. Specify probability distributions of the independent variables.

3. Run simulations repeatedly, generating random values of the independent variables.

We can run many Monte Carlo Simulations by modifying the parameters we use to simulate with taking into consideration that smaller variances are better.

The MC method has applications such as Particle physics also Simulations can be extremely helpful for the optimization of SPECT and PET cameras, image formation in the nuclear medicine.

4.1. MCNPX

- What is MCNPX?

MCNP: It is a general Monte Carlo Code for N-Particle Transport and MC transport code MCNP. <u>And we use MCNP to solve particle transport problems as it can be used in solving one particle transport problem or more than one particle.</u>

And it uses a continuous energy scheme without using energy groups. As it can perform criticality calculations and it has extensive cross section libraries

User Input to the Code

The user creates an input file that is read by MCNP.
This file contains information about the problem in areas such as:

1. Geometry specification
2. Material descriptions

3. Location and characteristics of the source
4. The type of tallies desired

The format of the input extremely specific. Three major sections:
1. **Cell cards:** used to describe the shape and material content of physical space.
2. **Surface cards:** for the boundaries in space used to “create” cells (spheres, cylinders, planes)
3. **Data cards:** for sources, materials, and tallies.

Available software packages for simulation radioactive particle transport: (MCNP-EGS4 -Geant)

5. Dose Calculations.

Before defining the Goal of the dose limit and its concept we first need to differentiate between radioactivity and exposure to know how the dose calculations work and how to know the dose limit:

Table 1. This table shows the difference between the radioactivity and the exposure

Radioactivity	Exposure
1- the amount of ionizing radiation released by a material. Whatever the radiation type is.	1- the amount of radiation traveling through the air as various radiation monitors measure exposure.
Activity represents the number of atoms in the material that decay in given time period with units (Ci and Bq)	2- the units used for describing the exposure are the roentgen (R) and coulomb/kilogram (C/kg)

The use of **table 1**. will ensure that the exposure is being well understood to do the dose rate calculations which will help us, so the radiological protection is being done in a right way when we will use mathematical simulation to know what the distance from the source is where the radiation will be dangerous according to international standards.

5.1. Dose Limits

ICRP is:

1- Primary body in protection against ionizing radiation.
2- An independent non-governmental organization

The ICRP provides recommendations and guidance on protection against the risks resulting from ionizing radiation, for both artificial and natural sources used in various fields.

- The ICRP system of radiation protection is based on three fundamental principles**: justification, optimization, and dose limitation**.

1- justification is about that radiation exposure in the different practices should cause more good than harm.
2- Optimization requires that the likelihood of incurring exposures, the number of people exposed, and the amount of their individual exposure should all be kept **A**s **L**ow **A**s **R**easonably **A**chievable (**ALARA**).
3- Dose limitation: This principle requires that the dose to individuals from planned exposure situations, should not exceed a certain value and these appropriate limits recommended by the Commission.

ICRP is composed of a Main Commission and five standing Committees on: radiation effects, **doses from radiation exposure**, protection in medicine, the application of ICRP recommendations, and protection of the environment.

Radiation dose: a measure of the amount of exposure to radiation. In radiological practice, three types of doses are fundamentally used, shown in Table 2.

Table 2. The three types of doses commonly used (Absorbed, Effective and Equivalent doses).

Absorbed dose	**Equivalent dose**	**Effective dose**
a physical quantity that can be measured	calculated for individual organs. It is based on the absorbed dose to an organ, adjusted for the effectiveness of the type of radiation.	calculated for the whole body. It is the addition of equivalent doses to all organs, each adjusted to account for the sensitivity of the organ to radiation.
The unit: milli grays (mGy).	The unit: millisieverts (mSv) to an organ.	The unit: millisieverts (mSv).

- equivalent dose and effective dose are used for the sake of radiological protection. (That is what we are concerned here)

  - Sievert: is a unit of radiation exposure dose that a person receives.
  - The larger the value is the higher the exposure is.

ICRP publication 103 classified three categories of exposure situations (ICRP 2007)

1- planned exposure situations which involve operation of sources.

2- emergency exposure situations, which require urgent action to avoid or reduce undesirable consequences
3- existing exposure situations, which include prolonged exposure situations after emergencies.

  - The ICRP recognizes three categories of exposure are known as occupational, public, and medical exposure.

- **Occupational exposure**: for the radiation exposure of individuals as a result of their work, only those exposures that can reasonably be regarded as the responsibility of the operating management are included.

- **Medical exposure:** is about the exposure of patients and exposures to all who work on the field.

- **Public exposure:** is any exposure other than medical and occupational.

The principles of justification and optimization are applied to all three categories of exposure (planned, emergency and existing), but dose limits apply only to planned exposure situations.

- **The 2007 Recommendations of the International Commission on Radiological Protection ICRP Publication 103 Approved by the Commission in March 2007.**

- These recommendations are not the same for all people as we mentioned in the last section the ICRP classified the exposure to three categories so, firstly exposed workers have a dose limit with maximum effective dose 20 mSv a year, and with **equivalent dose to the lens of the eye** 20 mSv a year, mSv [2] (updated later) and for the maximum **equivalent dose to the skin, the hands and feet** (averaged over 1 cm^2) is 500 mSv in a year.

The ICRP recommends that occupational exposure of pregnant women should fall into the limits similar to that of the public.

Public **effective dose** one mSv a year (higher values are permitted if the average over five years is not above one mSv a year) **the equivalent dose to the lens of the eye** fifteen mSv a year **the equivalent dose to the skin** (averaged over one cm^2) fifty mSv a year.

Table 3 summarizes the values of the doses recognized as limits by category as stated above.

Table 3. Recommended dose limits (ICRP Publication 103).

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years	1 mSv in a year
Annual equivalent dose in		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	–

6. Our work.

Figure 6 presents an image obtained with the use of the MCNPX viewer of the geometric arrangement used in the simulation seen from two different planes. The numbers represent the different cells that make up the constructed geometry. The approximate dimensions of a classical preclinical system, the same materials with their chemical elements and densities, and other characteristics have been used to recreate the geometry. The energy spectrum and other characteristics of each type of radiation according to the arrangement were considered.

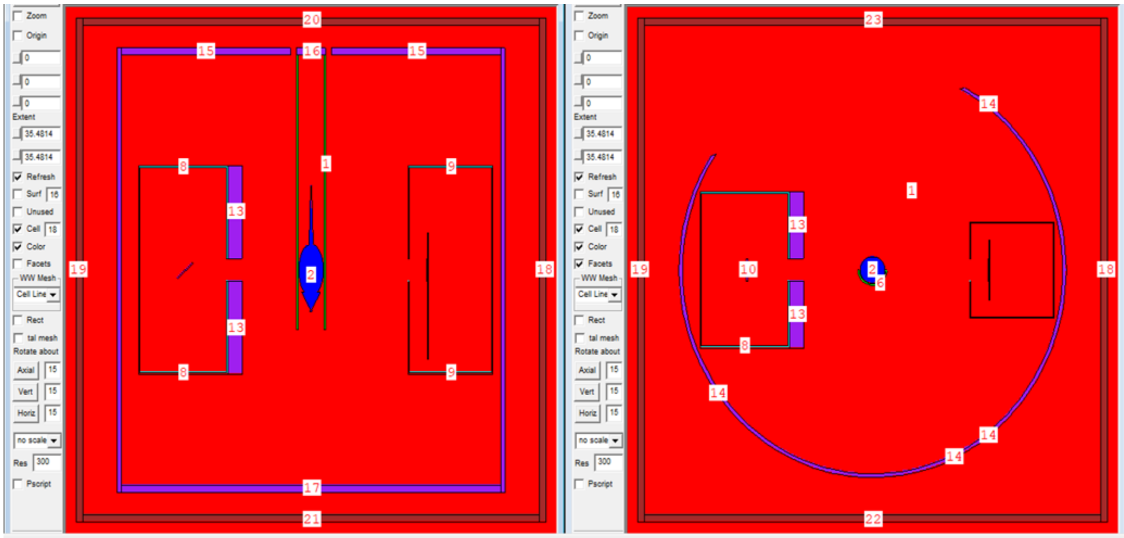


Figure 6. Schematic representation of the geometric arrangement considered in the calculations.

7. Results

7.1. CT

Figures 7 and 8 present the results obtained in the CT tomography simulation in the form of dose rate with the distance from the center of coordinates dependencies for different Pb wall thicknesses introduced as shielding and protection. The analysis of these graphs allows to arrive at the following ideas.

For the CT with no lead wall the minimum safe distance is so high and the variation with using the Pb is extremely high as with 0 cm Pb wall thickness the minimum safe distance is around ~ 3615 cm. For Pb with thickness 0.05 cm the minimum safe limit ~ 1570 cm.

For 0.1 cm the distance falls to be around 725 cm but with increasing the lead wall as in about thickness 0.5 cm and larger ones we get far less than the reference dose limit, so the safe distance falls to be in order of few cm (30-40), as for 0.3 cm the distance becomes around 78 cm, for 0.5 it becomes 38 cm and for 1 cm it is ~ 34 cm, for 2 cm Pb wall it is ~ 32 cm, so from the results we can say that the role of lead in the shielding process is crucial for the CT as it can give attenuation percentage ~ 99%

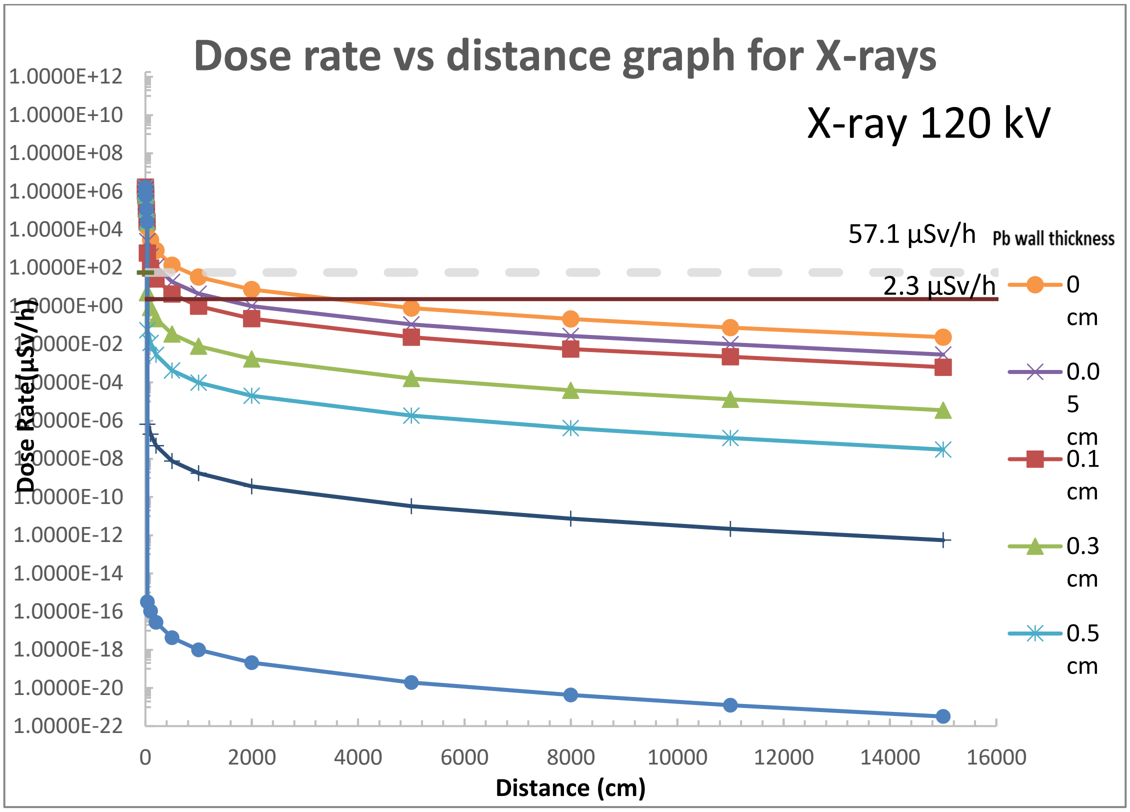


Figure 7. Dose rate vs distance graph for X-rays.

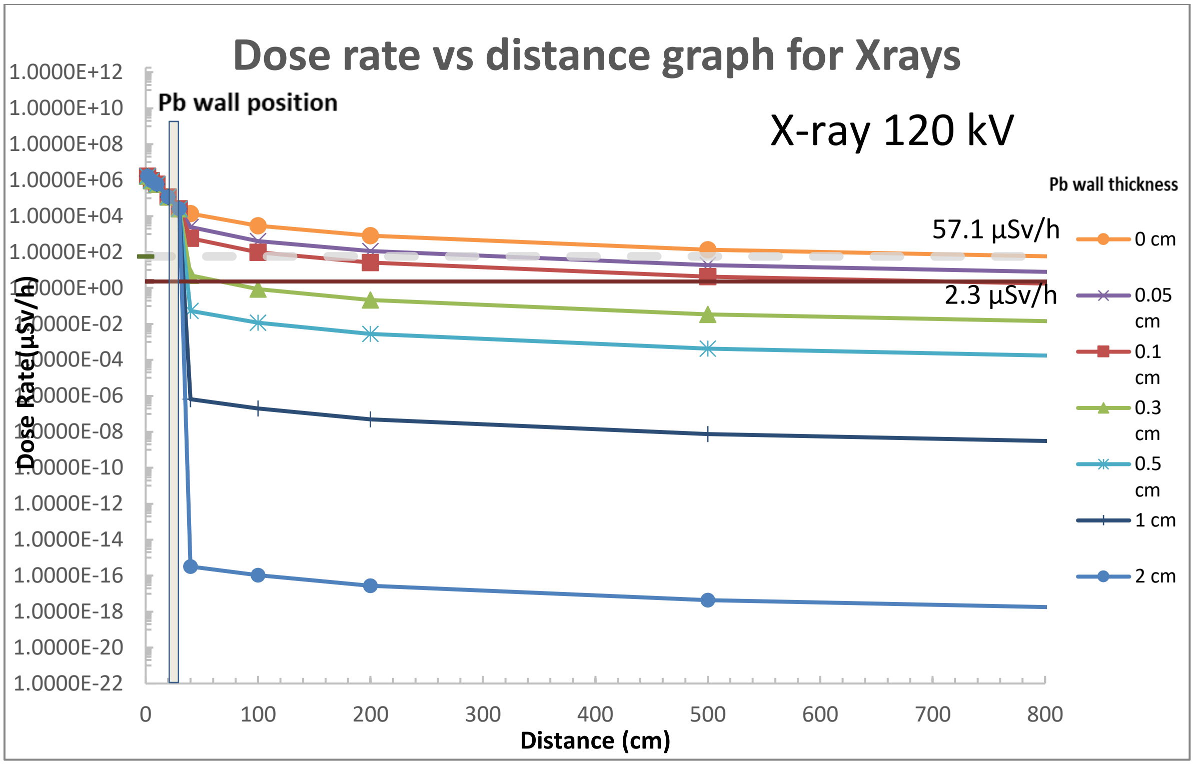


Figure 8. Zoom of figure 7 of dose rate vs distance graph for X-rays.

7.2. SPECT

7.2.1. ^{99m}Tc

For SPECT using ^{99m}Tc source, it is seen in **figure 9** that at 20 cm from the center of coordinates, the dose rate falls to the safe limit. Pb wall is at 35 cm, and it helps in reducing the dose rate, but it is not necessary to use the Pb wall in the SPECT arrangement unlike the CT.

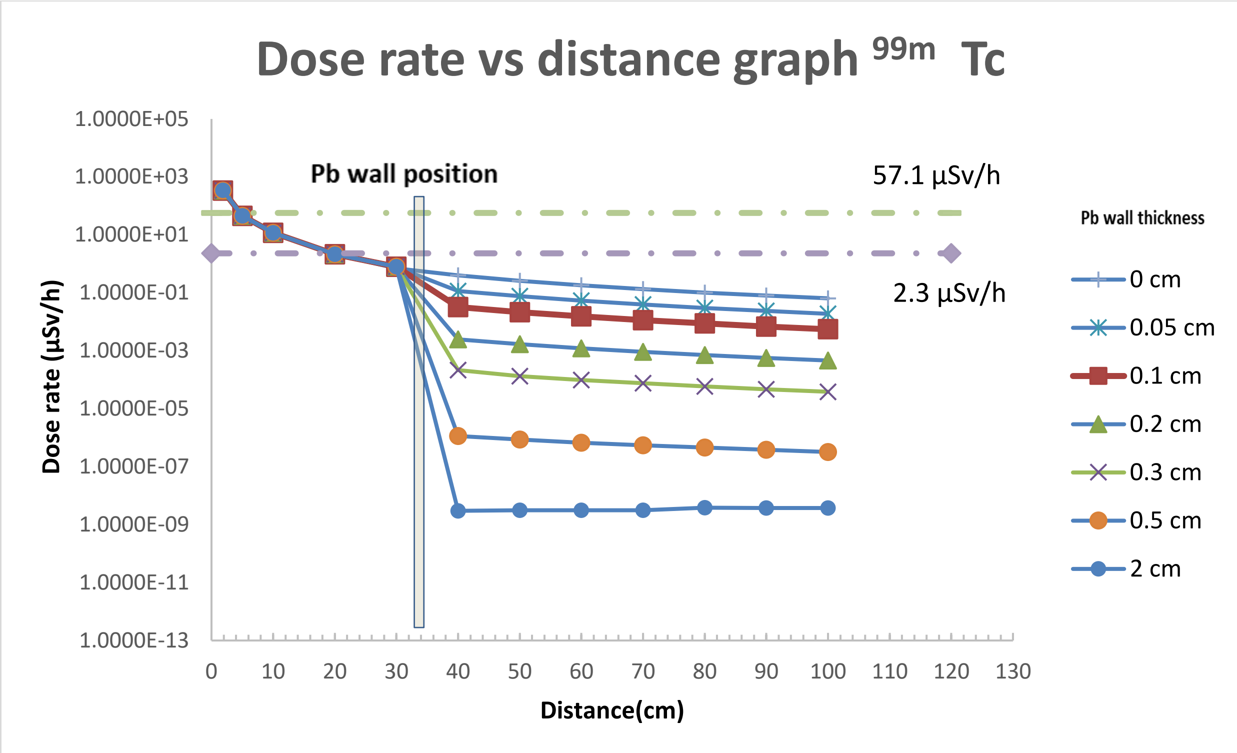


Figure 9. Dose rate vs. distance behavior calculated for ^{99m}Tc source.

7.2.2. ^{131}I

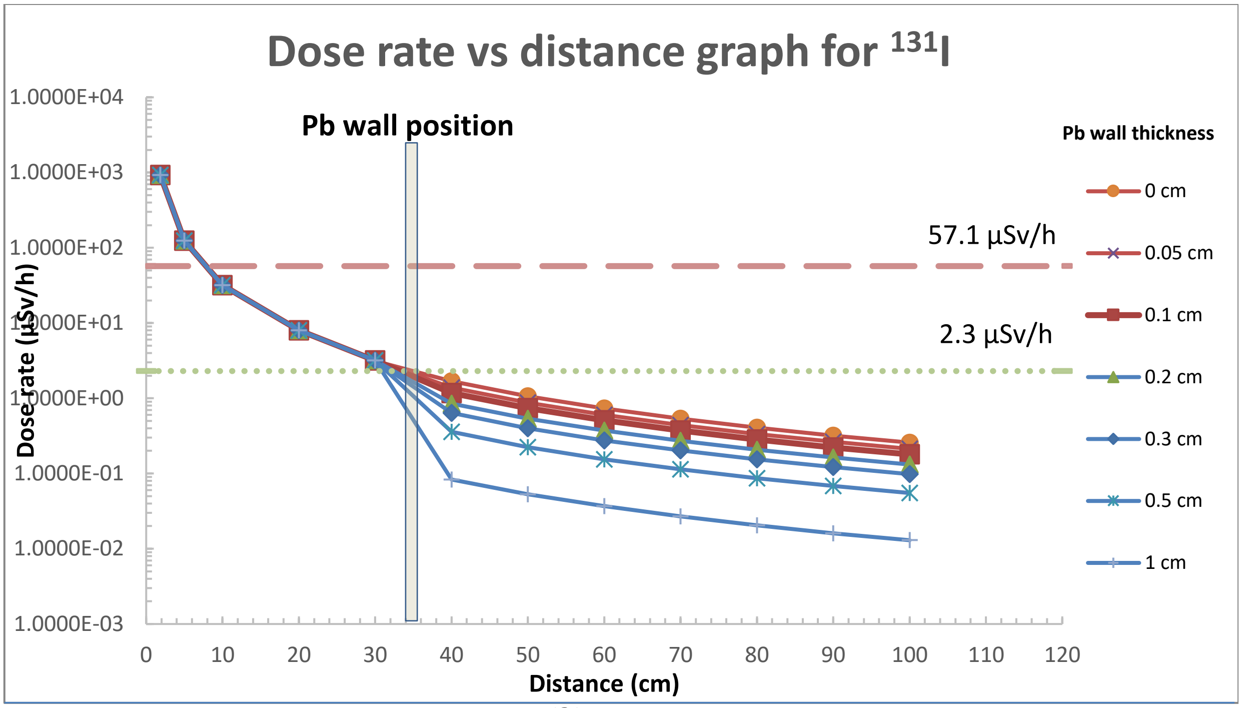


Figure 10. Dose rate vs distance graph for ^{131}I.

For the lead wall thickness= 0 cm, the safe dose limit is ~38 cm, for Pb with thickness= 0.05 cm the safe distance is ~ 36 cm and for Pb with thickness= 0.1 cm the safe distance is ~ 34 cm and for Pb with thickness= 0.2 cm the safe distance is ~ 32 cm and for Pb with thickness= 0.3 cm the safe distance is ~ 33.5 cm and for Pb with thickness= 0.5 cm the safe distance is ~ 32.5 cm and for Pb with thickness= 1 cm the safe distance is ~ 32 cm. Evidently, in this case, a Pb wall thickness of 0.1 cm located 35 cm from the source is sufficient to guarantee that to the right (outside) of this shielding the dose rate is safe for occupationally exposed personnel.

6- Conclusion

In our work by using the MCNPX code for the simulation of radiation transport in materials, the dose rate distribution was studied in a SPECT/CT preclinical scanner. Two sources used in these devices were discussed above.

With the goal of determining the minimum distance to the source that can be considered safe, minimum permissible distances for the skin and cornea of the eyes were determined.

SPECT: When ^{99m}Tc is used as photon source, the presence of the lead wall wasn't that necessary, as it is possible to construct a simple preclinical SPECT device with no protection walls 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. In the case of using ^{131}I, a thin layer of 0.1 cm of Pb is enough to guarantee the safety of the personnel.

CT: Calculations of radiation attenuation in the lead wall with different thickness were determined which lead to attenuate the radiation in a large percentage ~ 99%.

From the obtained results we can tell that it is necessary to use 0.5 cm lead protection, and sometimes it is not giving the necessary protection against radiation, so in this case we must use other methods of protection.

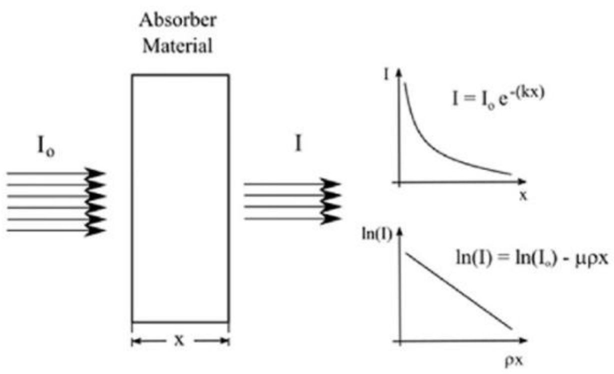


Figure 11 Beer- Lambert attenuation law for a monoenergetic gamma ray beam of intensity I passing through an absorber of thickness x. Exponential decay representation of I versus x and of ln(I) versus path length (px).

Acknowledgement:

I want to thank Dr Antonio for being such a great mentor, he was so helpful and however I needed he prioritized my learning process and all comes between, it’s not easy to find such a professor who is good at what he is doing and at the same time he dedicates his time for helping younger students, so I am grateful for being one of his students and I hope to be given the opportunity to work with him again.

7- References

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