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

This paper will look at modelling the interaction of radiation with matter, using a Monte Carlo based code systemMCNPX, using the example of an SPECT and CT scanner. Their geometry, components, materials and dimensions were taken into account in the simulation. Also, the most widely used radioisotopes were chosen: 201Tl, 99mTc, 131I, which were used as gamma ray sources.

The output characteristic is the dependence of equivalent dose rate on various given conditions. Taking into account that there are international requirements of radiation protection, the calculated dose rates for different conditions were compared with the limit values of safe dose rates, for different categories of population.

Based on the data of the calculations obtained, graphs were plotted, plant diagrams were made, and the resulting dose rates were compared with the permitted dose rates.

INTRODUCTION

Developments in science and medicine have proved that ionisingradiation does not only bring harm, but can also be channelled in a positive way. Ionisingradiation - is a combination of different types of microparticles and physical fields that have the ability to ionisematter, i.e. to form electrically charged particles called ions.

However, every device that uses any source of ionisingradiation in its operation must necessarily guarantee its safety for the health of the occupationally exposed personnel.

During design, development and before commissioning tests are carried out to ensure that the equipment is as harmless to human health as possible.

Among diagnostic and treatment methods using ionizing radiation, both conventional X-ray machines as well as sophisticated gamma cameras or PET and SPECT scanners are of particular importance.

But such studies would not be possible without mathematical modelling of radiation transport; see e.g. [1, 2].

The main aim of this work is to determine the working distance that is considered safe for occupationally exposed personnel, using the MCNPX code system based on the Monte Carlo method.

In pursuing this objective, the following sub-objectives are to be achieved:

- To become familiar with SPECT and CT imaging techniques.

- To study methods of mathematical modelling of radiation-matter interaction.

- Define the safe dose limits for occupationally exposed staff and patients according to the literature data.

- Use MCNPX software to determine dose rates near two preclinical scanners, CT and SPECT, for different sources and geometric arrangements.

- Determine the minimum safe distances for occupationally exposed personnel when working with these scanners from the simulation results.

MATERIALS AND METHODS

Medical Imaging Techniques (MITs) are non-invasive methods for looking inside the body. It used to assist diagnosis or treatment of different medical conditions.

The concerning techniques are X-ray Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Radionuclide imaging, that includes (Scintigraphy, Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT)).

In this report we will look at X-ray Computed Tomography (CT) and Single Photon Emission Computed Tomography (SPECT).

Computed Tomography (CT) is a diagnostic technology that combines X-ray equipment with a computer and a cathode ray tube display to produce images of cross sections of the human body. Computed Tomography uses a method of the cross-sectional images (slices) of the body.

Inside the CT scanner, there is a rotating frame that has an X-ray tube mounted on one side and the detector mounted on the opposite side, and they spin in circles. Each time the X-ray tube and detector make one complete rotation, an image or slice is acquired.

Advantages:

- non-invasive, quick and painless;
- global view of veins/arteries;
- good spatial representation of the physiology.

Disadvantages:

- using of ionising radiation;
- no real time information.

With a CT scanner, it is possible to distinguish between tissues with a density difference of 1%.

Single Photon Emission Computed Tomography (SPECT) is aradionuclide imaging technique that relies on drugs that are labelled with atoms that emit at least one gamma ray when they decay. The name SPECT came from the fact that the radionuclides used in the gamma camera mostly emit one principal photon per radioactive transition. SPECT machines combine a number of gamma cameras that rotate around the patient. Gamma rays are normally emitted equally in every direction, so it is necessary to use a collimator in front of the detector that allows only the gamma rays emitted in the direction of the detector to be registered. By moving the detector completely around the patient, a 360º image is obtained.

Advantages:

- gives functional information;
- good tissue contrast;
- global view of the system of interest;
- cancer progression can be monitored.

Disadvantages:

- using of ionising radiation and radioactive materials;
- high cost;
- low spatial resolution.

Both the CT and SPECT techniques can be used at the same time in the same scanner, which allows taking advantage of the benefits of each of these methods. This is how the modern SPECT/CT scanners arise.

Figure 1 shows a preclinical small animal SPECT/CT scanner, widely used in laboratories for the development of new drugs and sophisticated treatments, which can then be used in humans. Precisely this type of preclinical scanner, for small mice, is the target of our study in this work.

Fig. 1. Preclinical SPECTC/CT scanner images taken from [3]).

To simulate the interaction of radiation with matter, we used **MCNPX** software based on the Monte Carlo method.

Monte Carlo methods are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. The underlying concept is to use randomness to solve problems that might be deterministic in principle. They are often used in physical and mathematical problems and are most useful when it is difficult or impossible to use other approaches [4].

In our case, this method is able to recover with accuracy discordance in the radioactive doses caused by heterogeneity within the body of the patient. This occurs because the method of Monte Carlo allows that human tissues are characterized by elemental composition and mass density, and therefore allows the consideration of all atomic interactions.

MCNPX -MCNPX is a three-dimensional code using

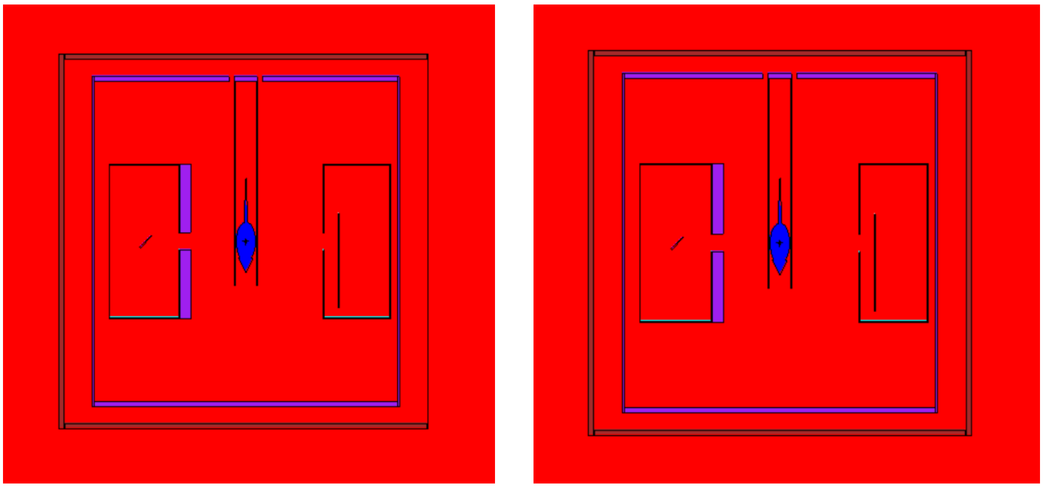
Monte Carlo method [5] of individual probability events, in a geometric given three dimensional configuration and with different material compositions. MCNPX is used in dosimetry, radiography, medical physics, nuclear criticality calculations, nuclear medicine etc.[6].

In order to work successfully with the software the user has to create an input file with all the information necessary to perform the simulation: the materials required, the geometry of the experiment, source characteristics. After taking into account all the conditions entered, the programme will generate an output file when the calculations are completed. All output data used from MCNPX is normalised by the number of incident particles from the source (or number of calculated histories) and are reported together with their estimated relative error.

In this work a large number of histories (1E6) were used to obtain adequate statistics.

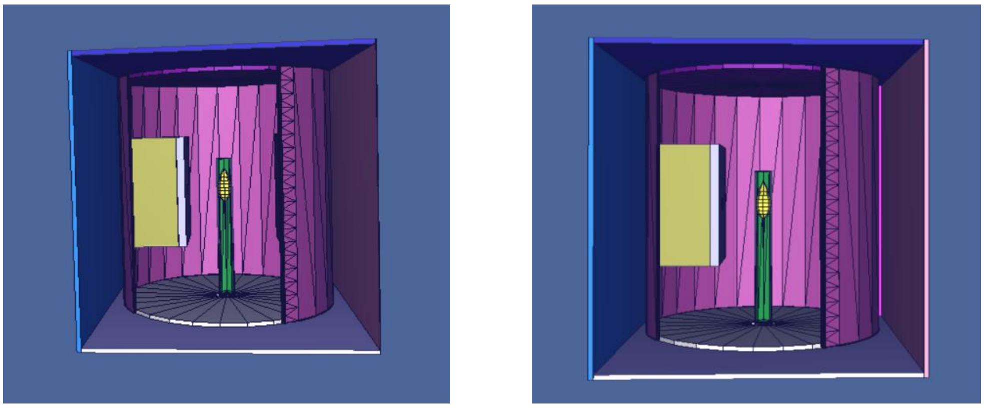
OriginLab was used to process the simulation data and create the graphical dependencies [7].

VisedXwas used to visualize the MCNPX input files, facilitating their understanding and modification. Examples of 2D and 3D graphical representations of modeled SPECT/CT scanner geometry obtained with the VisedX are shown below in Figures 2 and 3.



(a) (b)

Fig. 2.2D model of SPECT/CT scanner with lead wall thickness 0.1 cm (a) and 1 cm (b).



(a) (b)

Fig. 3. 3D model of SPECT/CT scanner for lead wall thickness 0.1cm (a) and 1cm (b).

DOSE SAFE LIMITS

Dose limits are set by the International Commission on Radiological Protection (ICRP)[8, 9]. They are necessary to prevent unreasonably high exposure of people to ionising radiation.

There are two groups: the general public and occupationally exposed workers.

Occupationally exposed workers

- Effective dose - 20 mSv a year;
- Equivalent dose to the eye lens - 20 mSv a year;
- Equivalent dose to the skin (averaged over 1 cm2) - 500 mSv per year
- Equivalent dose to arms and legs - 500 mSv per year.

Population

- Effective dose - 1 mSv per year
- Equivalent dose to eye lens - 15 mSv per year
- Equivalent dose to skin (averaged over 1 cm2) - 50 mSv per year.

To carry out this project, the dose limit corresponding to an occupationally exposed worker was chosen as the permitted dose limit, that is, a value of 20 mSv/year or 2.3 mSv/h.

RESULTS

In this work we considered the dose rate behaviour for X-rays (CT diagnostics) as well as for radionuclides 201Tl, 99mTc, 131I (SPECT diagnostics).

The nuclide and its energy were fed to the input, and the output was the effective dose as a function of distance for different lead protection wall thicknesses. The results were processed, and plots of the dose rate versus distance were plotted. The plots show the dose limit line (2.3 mSv/h) with intersection points for different cases, and the lead protection wall is also shown. The graphs obtained for the different nuclides are presented below.

SPECT

Figures 4-6 show plots of the resulting dose rate (mSv/h) versus distance (cm) for the 3 nuclides used in SPECT: 99mTc, 201Tl and 131I. We can see that when radiation passes the wall set at 33 cm, the dose rate is significantly reduced.

For a 99mTc source, a distance of 17.88cm was found to be safe, as shown in Figure 4. Due to the low energy of 99mTc, the absorption in air is sufficient to attenuate the radiation to safe dose levels, so the value of safe distance is the same for all cases considered.

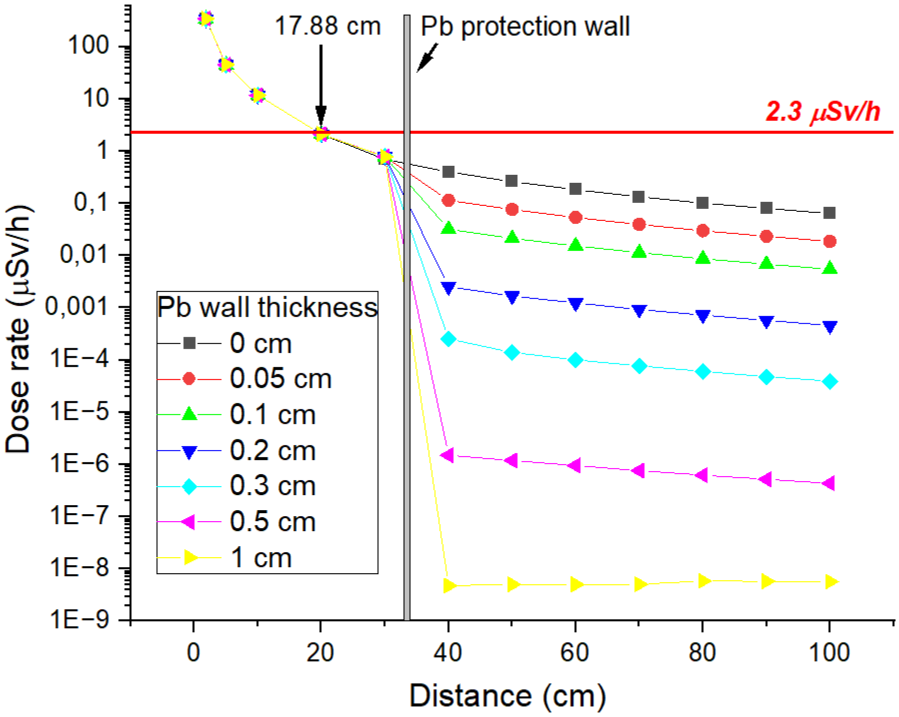


Fig. 4. Plot of dose rate (mSv/h) versus distance (cm) in SPECT for 99mTc.

Similar to 99mTc, the graph for 201Tl can be explained. The safety distance for 201Tl will be 13.15 cm, as shown in Figure 5.

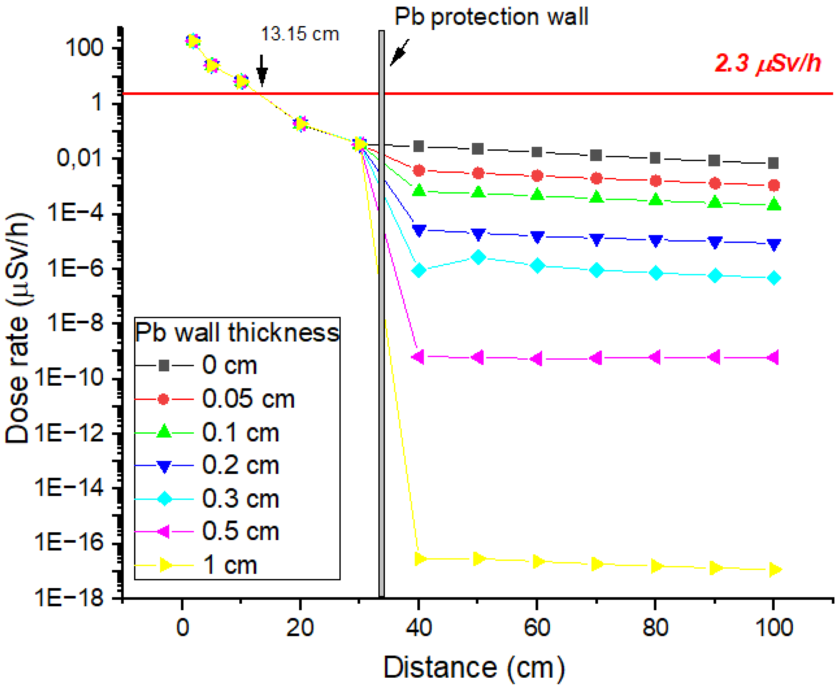


Fig. 5. Plot of dose rate (mSv/h) versus distance (cm) in SPECT for 201Tl.

The situation is slightly different in Figure 6 for 131I. Here, a different safe state is observed for the different parameters entered. So, with no wall the safety distance will be 35.05 cm and with a thickness of 1 cm it will be 30.92 cm.

From the above it can be concluded that the radiation dose rate attenuates when passing through a lead wall.

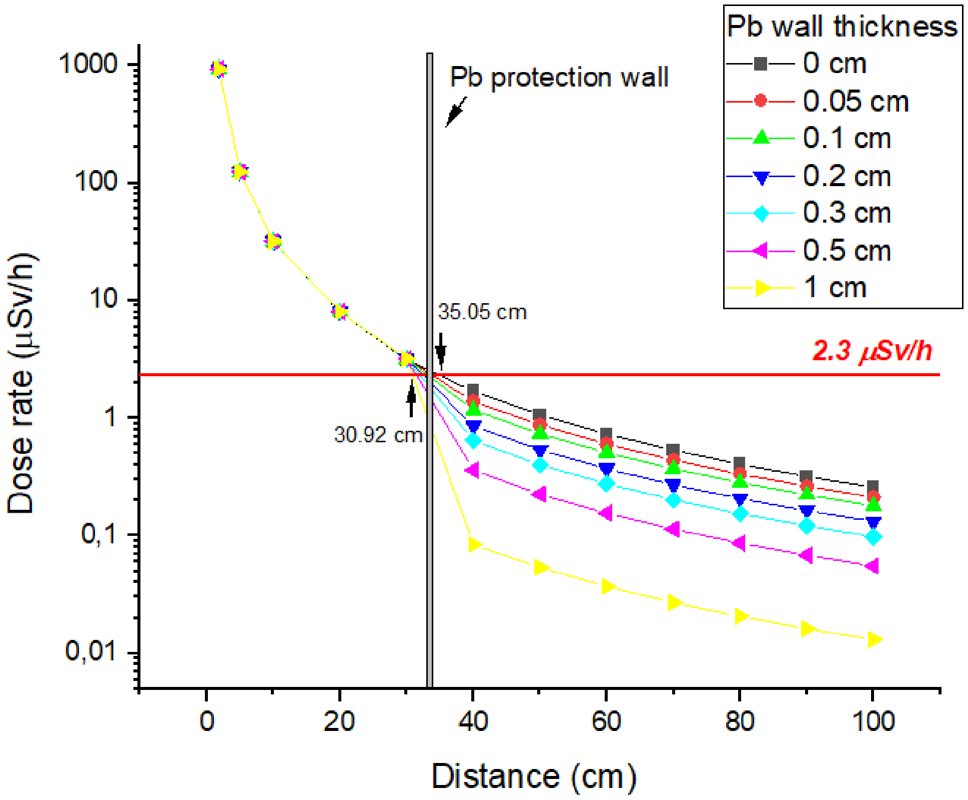


Fig. 6. Plot of dose rate (mSv/h) versus distance (cm) in SPECT for 131I.

CT – X-rays

Figure 7 shows the change in dose rate as a function of distance for the CT X-ray case as a function of the different lead wall thicknesses.

The safe distance for workers is 3590 cm in the case of no lead wall, 1369 cm for a thickness of 0.05 cm, and 673 cm for a thickness of 0.1 cm.

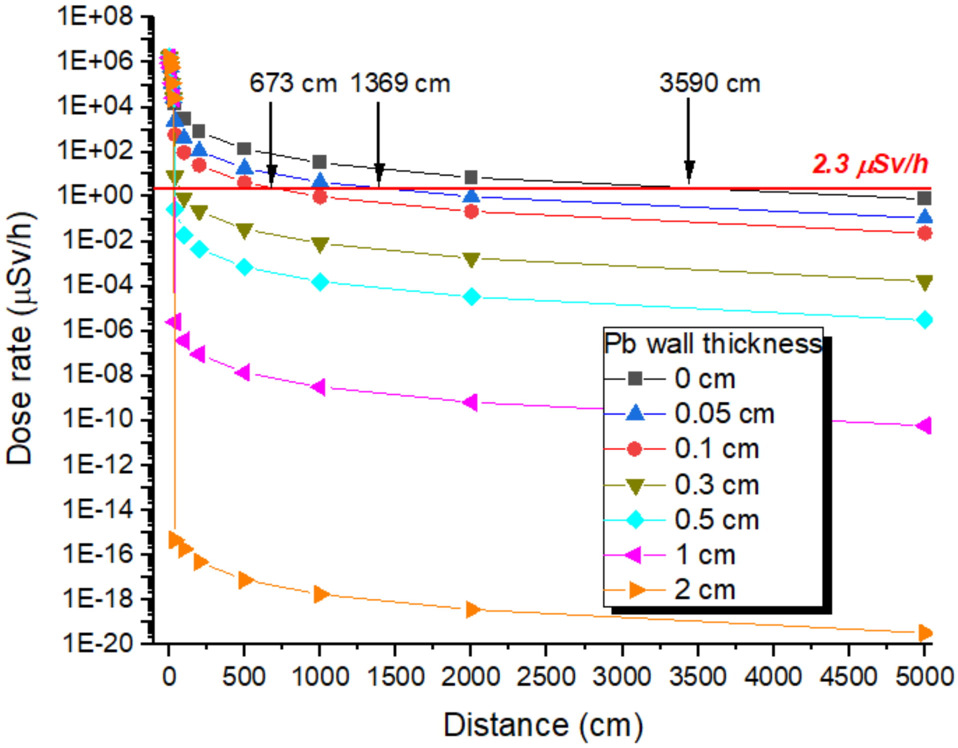


Fig. 7. Plot of dose rate (mSv/h) versus distance (cm) in CT for W X-ray tube.

Analysing the resulting graph, it can be concluded that an obstacle in the form of a lead wall with a thickness of 0.1 cm reduces the safe distance by ~ 81.25%.

CONCLUSION

In this paper we have used the MCNPX software to simulate the radiation pathway and dose rate distribution in SPECT and CT scanners under different initial conditions.

The result was the determination of the minimum safe distances for various nuclides used in SPECT diagnostics as well as for X-rays. Not only the nuclide energies but also the introduction of a lead wall of varying thickness into the experiment influenced the minimum distance values.

For SPECT the safe distance for radiation workers is at least 13.15 cm for 201Tl and 17.88 for 99mTc regardless of the thickness of the lead wall.

For 131I the safe distances depend on the availability and thickness of the wall. Thus, for no wall, the safe distance is 35.05 cm, for a thickness of 1 cm, it is 30.92 cm.

For CT the safe distance for radiation workers is 3590 cm in the case of no lead wall, 1369 cm for a thickness of 0.05 cm, and 673 cm for a thickness of 0.1 cm.

REFERENCES

[1] Nadrljanski M, Murphy A, Foster T, et al. Computed tomography. 2010. Reference article, Radiopaedia.org https://doi.org/10.53347/rID-9027

[2] Smith H, Chieng R, Mellam Y, et al. Single photon emission computed tomography (SPECT). 2018. Reference article, Radiopaedia.org https://doi.org/10.53347/rID-62599

[3] https://abteb.com/en/preclinical_products/nuclear_medicine/nanoscan_imaging_systems/nanoscan_spect-ct.php. Consulted on March 30, 2023.

[4] Monte Carlo method - Wikipedia. https://en.wikipedia.org/wiki/Monte_Carlo_method.Consulted on March 30, 2023.

[5] Waters LS, McKinney GW, DurkeeJW, FensinML, et al. The MCNPX Monte Carlo Radiation Transport Code. AIP Conference Proceedings, 2007; 896(1): 81. https://doi.org/10.1063/1.2720459.

[6] Hendricks J. S., LA-UR-08-2216, "MCNPX 2.6.0 Extensions", Los Alamos National Laboratory, April 11 (2008).

[7] OriginLab, Version*2023*. OriginLab Corporation, Northampton, MA, USA.

[8] The International Commission on Radiological Protection. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103, 2007.

[9] International Commission on Radiological Protection. ICRP Statement on Tissue Reactions / Early and Late Effects of Radiation in Normal Tissues and Organs – Threshold Doses for Tissue Reactions in a Radiation Protection Context. ICRP Publication 118, 2017.

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