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 medical imaging applications”

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Abstract

This project's objective is to study the use of Monte Carlo method in simulation of radiation-matter interactions for shielding evaluation in medical application. The main medical applications considered are SPECT and CT imaging techniques. The project aims to determine the safe permissible distance for workers in these applications to ensure their safety in their working environment. MCNPX was used for modeling the experiments. Multiple sources of radiation were simulated, and different Pb shielding thicknesses were evaluated relative to the dose rate of the respective source.

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Introduction

SPECT and CT are two of the most commonly used imaging techniques in the medical field. Each of them has different uses and benefits to provide. Their popularity emphasizes the importance of ensuring safety of workers using them according to the ICRP instructions.

Materials and Methods

SPECT

It stands for "Single photon emission computed tomography" and is a nuclear imaging modality frequently used in diagnostic medicine. SPECT produces a three-dimensional image of the distribution of a radioactive tracer (sometimes called a probe) injected into the bloodstream and subsequently taken up by certain tissues. This tracer emits gamma rays. Radiation is then captured by the gamma cameras of the SPECT system that gives data enough to investigate the performance of specific tissues.

Provided in Figure 1 some information about the characteristics of commonly used radioisotopes like:

- Iodine-131
- Technetium-99m
- Thallium-201

Principle: 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.

Nuclide	Half-life/h	Type of emission	Principal photon emission energies/MeV
^{123}I	13.2	Electron capture	0.16
^{99m}Tc	6	Isomeric transition	0.14
^{111}In	67.9	Electron capture	0.17/0.25
^{67}Ga	78.3	Electron capture	0.09/0.19/0.30
^{201}Tl	73.1	Electron capture	0.17

Figure 1: Data about Radioisotopes used in SPECT
https://www.researchgate.net/publication/46149818_Molecular_tracers_for_the_PET_and_SPECT_imaging_of_disease

Advantages:

- Shows activity of organs

- Low radiation exposure
- Cheaper (relative to CT)

CT

It stands for “Computed Tomography”, a computerized imaging method that depends mainly on the use of X-rays that is aimed at a patient producing signals that are processed by the machine’s computer to generate cross-sectional images, or “slices.” The successive slices are collected by the machine’s computer digitally that forms a 3D image of the patient that allows for easier identification of basic structures as well as possible tumors or abnormalities.

Principle: Based on the density of the tissue passed by the X-ray beam can be measured from the calculation of the attenuation coefficient. Attenuation values of the X-ray beam are later recorded by the computer and data is used to build a 3D representation of the scanned object/tissue.

Advantages:

- The ability to rotate the 3D image in space or to view slices in succession, making it easier to find the exact place where a problem may be located.
- Pain free
- Fast scan process

CT uses X-ray tubes to produce X-rays with energies in range (**20:150 keV**).

X-ray Tube:

Fundamental parts:

- filament (cathode): produces thermionic emission
- target (anode): stuck by electrons to produce X-rays

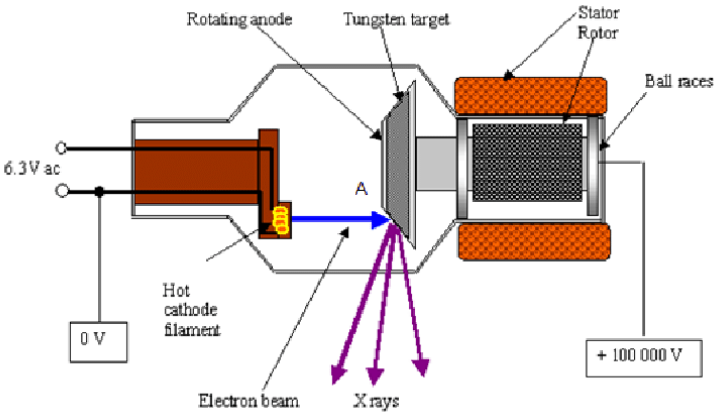

Figure 2: X-ray Tube Construction Illustration https://www.researchgate.net/publication/258310611_Advanced_ceramic_matrix_composites_for_high_energy_X-ray_generation

X-ray spectrum:

- Bremsstrahlung X-rays

Bremsstrahlung X-rays (meaning "braking" in German) are produced when electrons lose kinetic energy as they travel through the anode. The positively charged nuclei attract the electrons, causing them to lose energy, especially when they pass close to the nucleus. This results in the electron being deflected to a lower energy or even stopping completely.

The energy lost by the electron is converted into an X-ray, which is emitted from the anode.

- Characteristic X-rays

When electrons have energy equal to or greater than the binding energy of the electrons in the target atom, they can eject electrons from the atom, usually from the inner (K) shell. The ejected electron is called a photoelectron. To maintain atomic stability, the vacancy in the K-shell is filled by an electron from an outer shell. This transition between shells releases X-rays with specific energies, known as characteristic X-rays, which are unique to the binding energies of that atom.

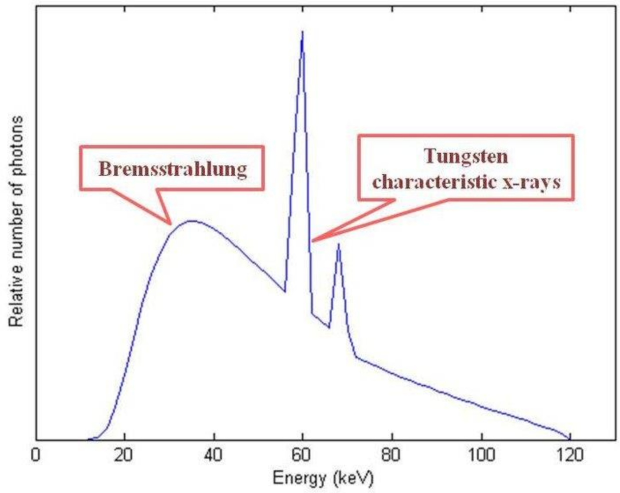

Figure 3: A graph example on the spectrum of X-rays https://www.researchgate.net/publication/257029228_Using_MARS_Spectral_CT_for_Identifying_Biomedical_Nanoparticles

SPECT – CT Comparison

	SPECT	**CT**
Type of Information obtained	Functional	Structural
Resolution	1-2 cm	1-2 mm
Radiation Dose	Low energy gamma radiation	Higher energy X-rays

Combined benefits of SPECT/CT

1. Better image quality
2. Detailed resolutions
3. Higher accuracy of malfunctions allocation
4. Reduced radiation dose
5. Reduced misdiagnosis error

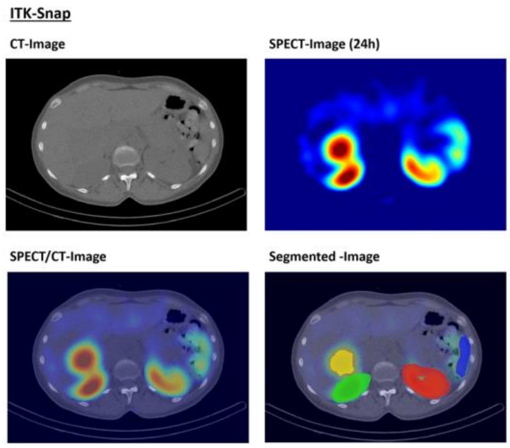

Figure 4: Different tomography scans applied on the same cross-section of the patient's body https://www.researchgate.net/publication/334478290_Technical_Report_Time-Activity-Curve_Integration_in_Lu-177_Therapies_in_Nuclear_Medicine

Clinical Microtomography Equipment

Preclinical microtomography equipment encompasses a range of advanced imaging technologies designed for research involving small animals. These systems allow scientists to visualize and analyze biological processes in vivo, facilitating drug development, disease research, and therapeutic evaluations.

Types:

1. **MicroCT**: also known as X-ray microtomography, a radiographic imaging technique that can produce 3D images of a material's internal structure at a spatial resolution better than 1micrometer to visualize and help in analyzing the internals of a material.

2. **MicroSPECT**: Similar to SPECT but utilizes lower energy tracers that can be suitable for rats and mice tomography.

Dose safe limits

Radiation safety dose limits are established to protect individuals from the harmful effects of ionizing radiation. For occupationally exposed workers, radiation dose limits are higher than those for the general public due to the nature of their work, which involves regulated exposure to ionizing radiation. According to Radiopaedia, the annual dose limit for these workers is typically 20 millisieverts (mSv) averaged over five years, with no single year exceeding 50 mSv. These limits are designed to minimize the risk of radiation-induced health effects, particularly stochastic effects like cancer, while allowing for safe operation in radiation-intensive environments. Specific dose limits also apply to particular tissues, such as 150 mSv per year for the lens of the eye and 500 mSv per year for the skin and extremities. These limits are based on recommendations by international regulatory bodies, such as the International Commission on Radiological Protection (ICRP), and aim to balance safety with occupational requirements.

Interaction of photons with matter

The interactions between photons and matter are essential to a wide range of scientific and engineering applications, including medical imaging and nuclear physics. As photons traverse materials, they can interact with the atoms and molecules in various ways, depending on their energy levels and the characteristics of the medium. These interactions can result in phenomena such as absorption, scattering, or transmission, which are critical for processes like radiation shielding, imaging, and energy deposition. The main types of photon interactions with matter include the photoelectric effect, Compton scattering, and pair production.

Photoelectric Effect

The photoelectric effect occurs when a photon strikes an atom and transfers all its energy to an electron, causing the electron to be ejected from the atom. This process typically takes place when the photon's energy is equal to or exceeds the binding energy of the electron within the atom. The ejected electron, referred to as a photoelectron, carries away the energy of the photon, leaving the atom in an excited state. The likelihood of the photoelectric effect occurring increases with lower-energy photons (usually in the range of a few keV) and with elements that have higher atomic numbers (Z), as heavier atoms generally have higher electron binding energies, making it easier for photons to dislodge electrons.

Compton Scattering

Compton scattering involves a photon colliding with a loosely bound or free electron, transferring part of its energy to the electron while scattering in a different direction. In contrast to the photoelectric effect, Compton scattering results in the photon losing only a fraction of its energy; it continues on with reduced energy and altered direction. This interaction is most significant for intermediate-energy photons (ranging from a few keV to several MeV) and is predominant in materials with lower atomic numbers. The energy lost by the photon is related to the angle at which it scatters, and the ejected electron often gains considerable kinetic energy. Compton scattering plays a crucial role in radiation detection and imaging techniques, such as scintillation detectors and gamma cameras.

Pair Production

Pair production is an interaction that occurs at very high photon energies (greater than 1.022 MeV, which corresponds to twice the rest mass energy of an electron). When a high-energy photon approaches an atomic nucleus, it can convert into an electron-positron pair. In this process, the photon ceases to exist, resulting in the creation of two new particles: an electron and a positron. This interaction requires a nearby nucleus to ensure conservation of momentum and energy. At high photon energies, particularly in heavy materials with high atomic numbers, pair production becomes the dominant interaction mechanism. The newly formed electron and positron can also engage in further interactions, such as ionization and additional scattering events.

Monte Carlo method

The Monte Carlo method is a computational approach that employs random sampling to estimate numerical outcomes and tackle complex problems, especially when conventional analytical techniques are not practical or feasible. By generating random samples and applying statistical principles, this method enables researchers to approximate solutions across various fields, including physics, finance, and engineering. It is based on the law of large numbers, which states that the accuracy of estimates increases as more random samples are collected. This characteristic makes it particularly useful for addressing issues involving uncertainty, high-dimensional spaces, or systems that are too intricate for precise solutions.

In physics, the Monte Carlo method is extensively utilized to simulate systems with numerous interacting particles, such as gases, liquids, and solids, where exact solutions are often elusive. One of its main applications lies in statistical mechanics, where it assists in modeling the behavior of physical systems at a microscopic level by sampling different configurations and calculating thermodynamic properties. Monte Carlo simulations are also crucial in quantum mechanics for examining particle interactions, quantum states, and phenomena like phase transitions. Furthermore, this method is vital in fields such as neutron transport, radiation shielding, and materials science, allowing scientists to investigate complex physical phenomena and analyze systems under various conditions that would be computationally infeasible using traditional methods.

MCNPX for modeling radiation transport in matter.

MCNPX (Monte Carlo N-Particle eXtended) is an advanced simulation software that utilizes the Monte Carlo method to model the behavior of particles as they travel through various materials. By employing random sampling techniques, it effectively tracks how different types of particles interact with matter, making it a crucial resource for analyzing intricate radiation phenomena.

This tool is extensively applied in radiation transport simulations, using the Monte Carlo approach to depict particle interactions with matter. It follows the trajectories of individual particles as they experience various interactions, including scattering, absorption, and emission, within the modeled environment. MCNPX generates random samples based on probabilistic interactions informed by cross-sectional data, allowing it to simulate the movement of neutrons, photons, electrons, and other particles through complex geometries and materials. Each particle's path is calculated incrementally, taking into account the specific conditions at every interaction point, resulting in a detailed and statistically reliable representation of radiation transport.

The Monte Carlo technique employed by MCNPX involves monitoring individual particle histories—such as energy loss, direction changes, and types of interactions—in a probabilistic framework. This capability enables highly accurate simulations of radiation transport even in systems with complex geometries and diverse material compositions. The method encompasses a wide array of interactions based on comprehensive physics models, including elastic and inelastic scattering, photoelectric absorption, and pair production. By conducting numerous simulations, MCNPX produces statistically significant results that can be utilized for analyzing dose distributions, radiation shielding effectiveness, and particle flux within the system. This probabilistic methodology is particularly advantageous for scenarios where analytical solutions are unfeasible due to geometric complexity or irregularity.

Results

SPECT

This experiment was modelled using MCNPX with different sources having different energies to find the correlation between the dose rate and the distance away from the source.

Technetium-99m $(140.5\ keV)$

Using Microsoft Excel for interpolation, the safe distance for the safe dose rate limit was calculated to be $23.5\ cm$ away from the source as shown in Figure 5. Also, it was found that safe distance is the same for all thicknesses of the lead wall and without it which shows that the Pb wall is not required for the safety of workers in this experiment.

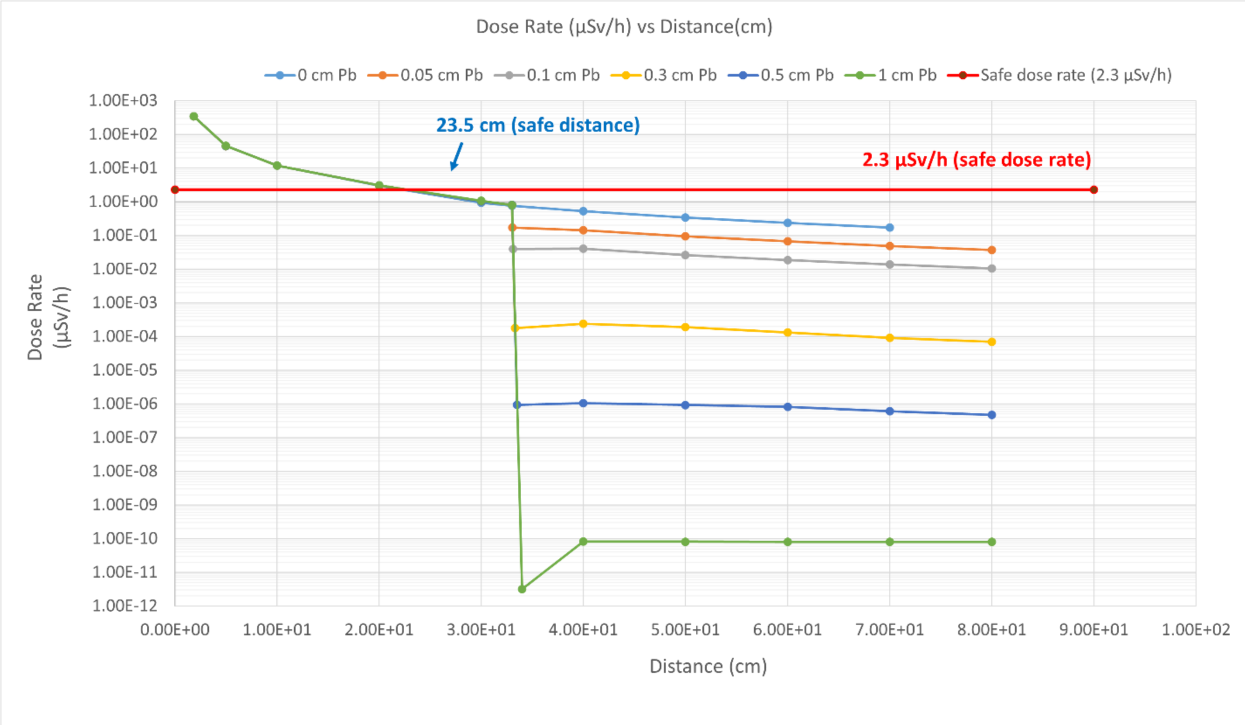

Figure 5: SPECT simulation results for 99mTc source

Iodine-131 (363 keV)

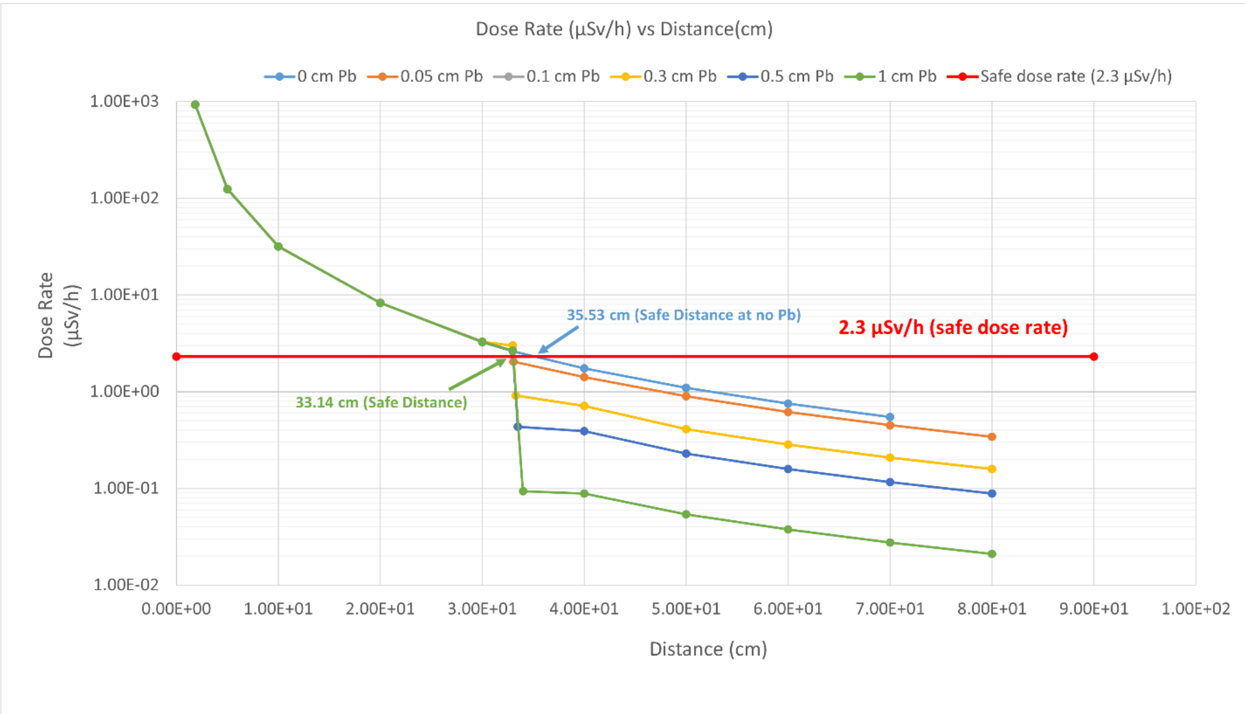

Figure 6: SPECT simulation results for 131I source

The same procedures were repeated for the Iodine-131 but the safe distance interpolated was different before and after when the wall was added. From Figure 6, It is inferred that the safe distance without the lead wall is 35.53 cm and with a lead wall (of any thickness in this experiment) is $33.14\ cm$ which illustrates a necessity for a lead wall to be used to secure the safety of the workers.

Thallium-201

For the 201-Tl source, it was deduced that the safe distance is $18.88\ cm$ before and after adding the lead wall which means that the Pb wall in this experiment is not essential for protecting working individuals.

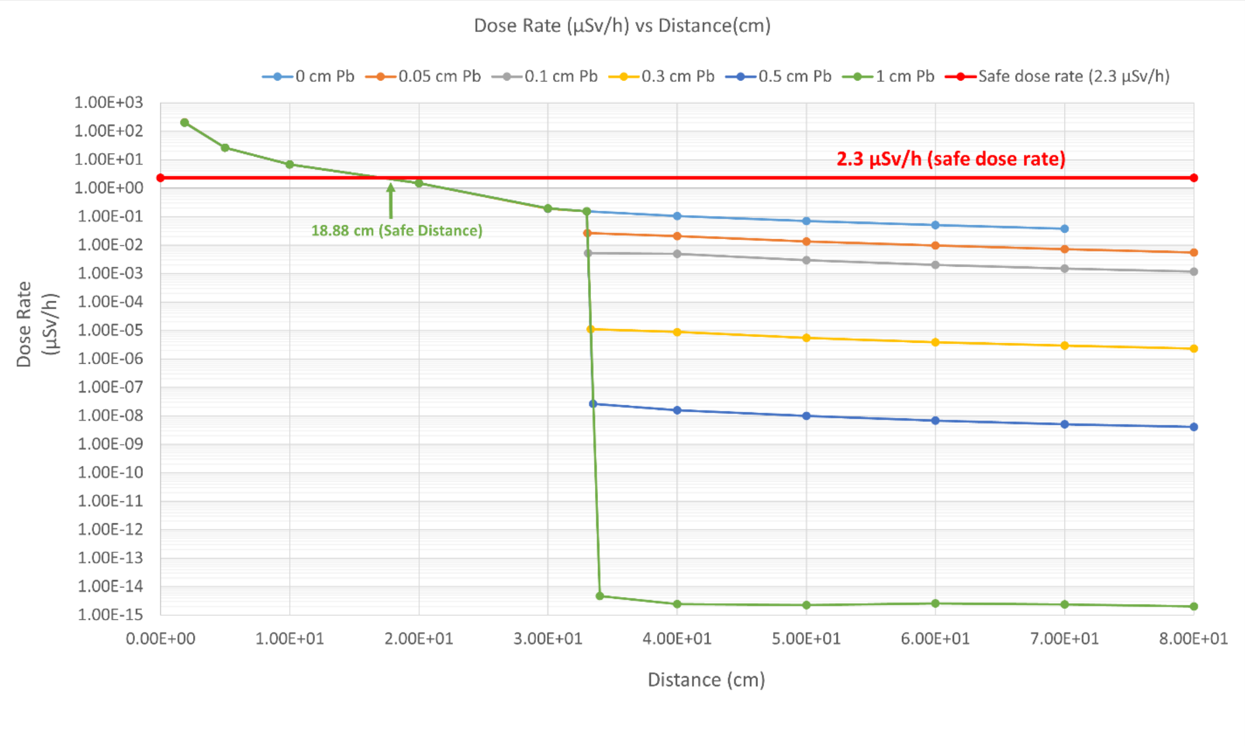

Figure 7: SPECT simulation results for 201Tl source

Based on the results data, it was found that when 99m-Tc and 201-Tl sources were used, it was unnecessary to use the Pb wall as a protective barrier. The very low values of dose rate mean that the safe working distance is located even before the wall. This was not the case for the 131-I source where a Pb wall of a suitable thickness is necessary to be used to ensure safety of the workers.

<u>CT</u>

Similar steps were carried for the CT to get the correlation between the dose rate of X-rays and distance.

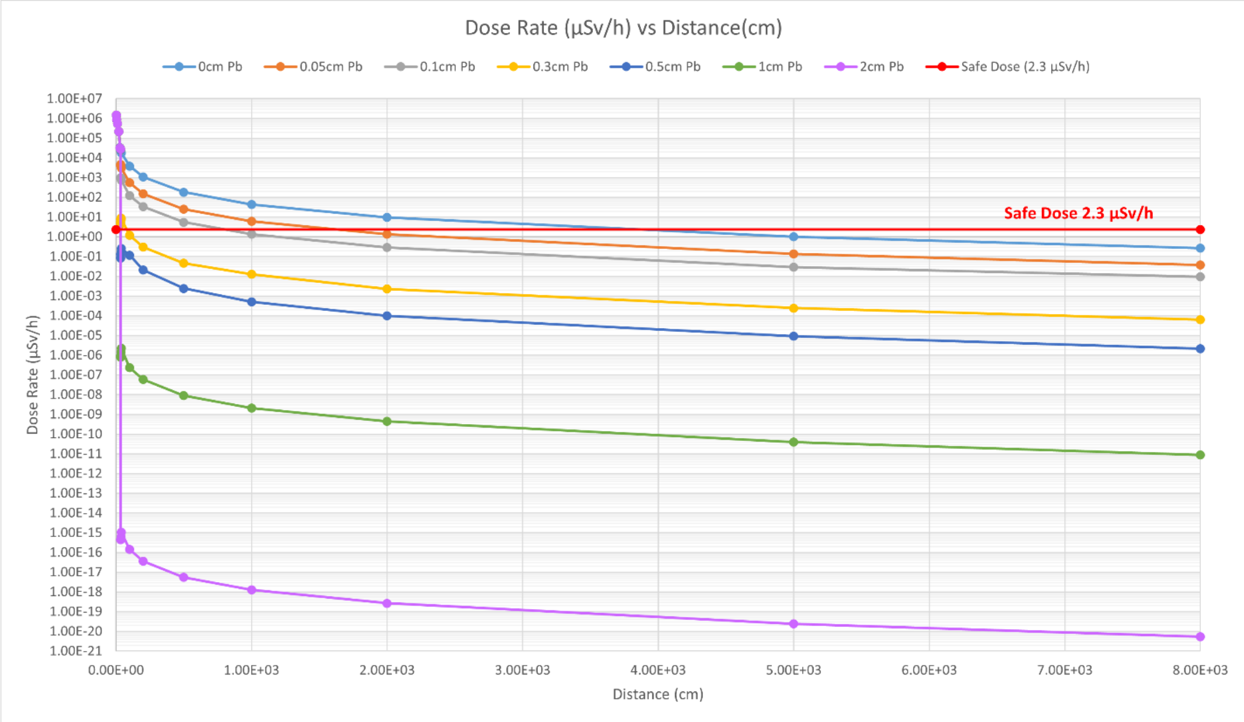

Figure 8: CT simulation results

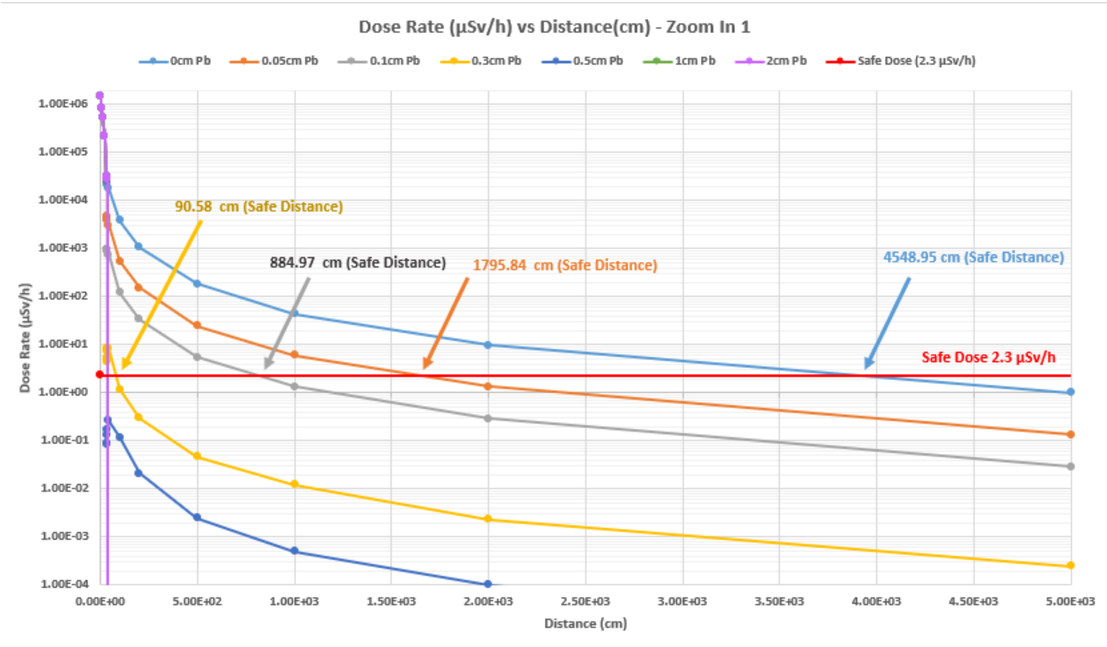

Figure 9: CT simulation results (Zoomed view 1)

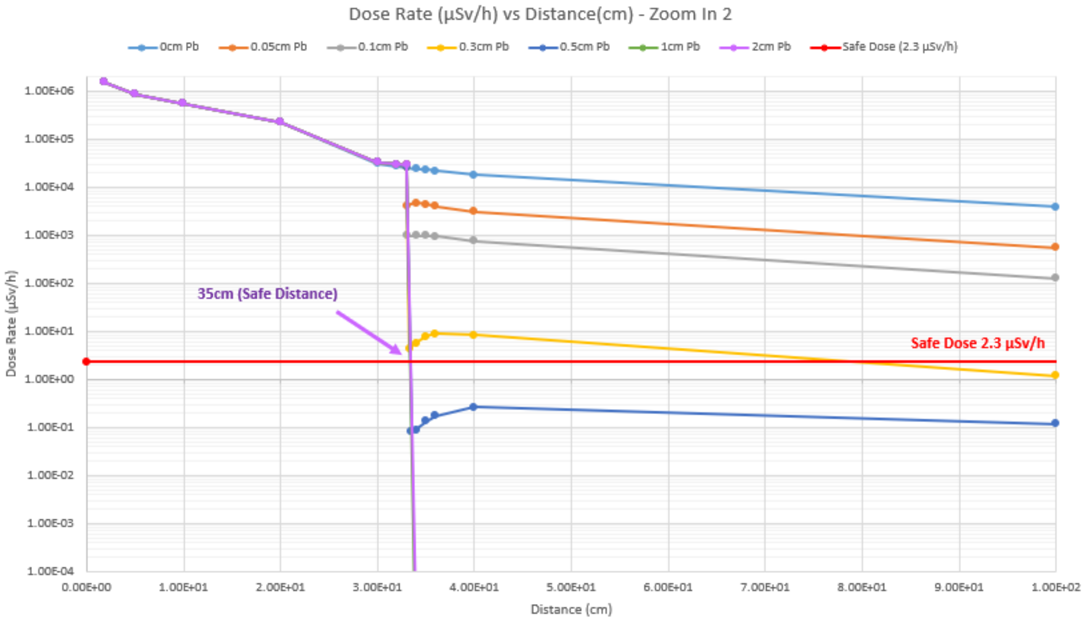

Figure 10: CT simulation results (Zoomed view 2)

CT results shown in Figure 9 and Figure 10 – which represent zoomed views of Figure 8 – illustrates that for the X-ray case the safe distance limit differs based on the thickness of the protective Pb wall. Observed from Figure 9 and Figure 10, the safe distance limit for a $2.3\ \mu Sv/hr$ dose is:

- $4548.95\ cm$ for $0\ cm$ Pb wall thickness (meaning no Pb wall is present)
- $1795.84\ cm$ for $0.05\ cm$ Pb wall thickness
- $884.97\ cm$ for $0.1\ cm$ Pb wall thickness
- $90.58\ cm$ for $0.3\ cm$ Pb wall thickness
- $35\ cm$ for $0.5\ cm$, $1\ cm$ and $2\ cm$ Pb wall thicknesses

After calculating the safe distances for different thicknesses of the lead wall, it was better to be demonstrated using a graph to show this correlation, shown in the following graph:

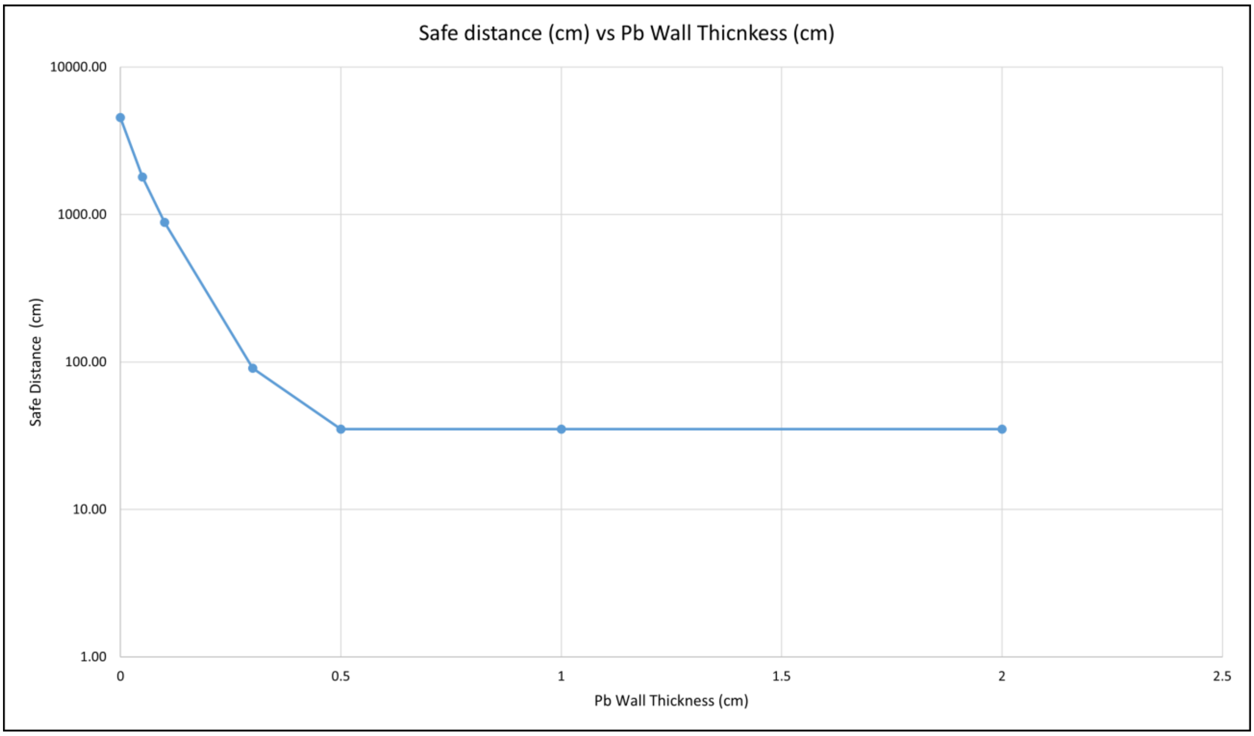

Figure 11: Correlation between Safe Distance and Wall thickness

In Figure 11, it was clearly observed that the decreasing values of the safe distance with respect to the increase in the thickness of the Pb wall. The figure illustrates that a thickness of $0.5\ cm$ of Pb or more is sufficient for the X-rays to be attenuated so that the dose rate does not exceed the safe values beyond the position of the wall. The dependency curve shown in the figure facilitates safe distance estimation for other values of Pb thicknesses which was not included in the present calculations.

It was noted that in the CT arrangement the dose rate values reached are much higher than when radiotracers are used in SPECT. This points attention to the vitality to take extreme measures and precautions to protect occupationally exposed workers and ensure their safety in their workplace. Additional measures include: the use of a suitable Pb wall (with a suitable thickness), special screens or curtains, lead aprons, concrete walls and lead glasses.

Conclusions

Using MCNPX for modelling experiments involving exposure to radiation is vital for securing the safety of personnel in the workplace. It allows us to avoid radiological risks and accidents in addition to decreasing the stochastic danger of radiation. In the SPECT experiments, different sources that have different energies were simulated and it illustrated the importance of estimating safe distance limits as for some sources it was required to have a lead wall with a certain respective thickness.

For the CT experiments, it was shown that the dose rate values were more critical than in the SPECT experiments which puts emphasis on using safety precautions beside the possibility of using additional ones for the sake of providing a safe working environment. Also, a correlation was found between the safe distance limits and the thickness of the protective Pb wall where this correlation can change depending on the material of the protective layer used.

It is very important to maintain radiological safety in the workplace of SPECT and CT workers. So, virtually simulating such experiments involving photon sources – like γ-ray and X-ray sources – is a very important practice in this field.

References

Golestani, Reza et al. "Small-animal SPECT and SPECT/CT: application in cardiovascular research." *European journal of nuclear medicine and molecular imaging* vol. 37,9 (2010): 1766-77. doi:10.1007/s00259-009-1321-8

Harrison R. L. (2010). Introduction To Monte Carlo Simulation. *AIP conference proceedings*, *1204*, 17–21. https://doi.org/10.1063/1.3295638

Kasban, Hany. (2015). A Comparative Study of Medical Imaging Techniques. International Journal of Information Science and Intelligent System,. 4. 37-58.

Kroese, D.P., Brereton, T., Taimre, T. and Botev, Z.I. (2014), Why the Monte Carlo method is so important today. WIREs Comput Stat, 6: 386-392. https://doi.org/10.1002/wics.1314

Landis, E. N., & Keane, D. T. (2010). X-ray microtomography. *Materials Characterization*, *61*(12), 1305–1316. https://doi.org/10.1016/j.matchar.2010.09.012

Murphy, A. (2017). Dose limits. *Radiopaedia.org*. https://doi.org/10.53347/rid-53065

Nadrljanski M, Campos A, Chieng R, et al. Computed tomography. Reference article, Radiopaedia.org (Accessed on 17 Nov 2024) https://doi.org/10.53347/rID-9027

Nikjoo, H., Uehara, S., & Emfietzoglou, D. (2012). *Interaction of Radiation with Matter*. CRC Press.

Pelowitz, D. B., & Others. (2011). *MCNPX^{TM} User's Manual, Version 2.7.0*. Los Alamos, NM, USA: Los Alamos National Laboratory.

Smith H, Hacking C, Chieng R, et al. Single photon emission computed tomography (SPECT). Reference article, Radiopaedia.org (Accessed on 17 Nov 2024) https://doi.org/10.53347/rID-62599

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