JOINT INSTITUTE FOR NUCLEAR RESEARCH
Laboratory of Nuclear Problems

FINAL REPORT ON THE INTEREST PROGRAMME

Modeling of radiation shielding in a preclinical SPECT/CT scanner using based on Monte Carlo code system

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Abstract

Radiation can simultaneously be bane as well as boon for people. It can be disastrous when handled unchecked and it can be life saver when used appropriately. Medical physics makes use of radiation for numerous purposes. As important as it is for the humanity, the health of occupationally exposed personnel is at constant risk. It is, therefore, crucial to take adequate measures to prevent the health hazards caused by radiation to the professionals. The aim of the present work is to determine minimum distances considered safe for the personnel, from the radiation sources used in preclinical SPECT/CT scanners, and to see the effect of lead wall in these equipments in terms of attenuation percentages. MCNPX and Geant4 code systems are used for simulating the passage of radiation and to study the dose rate distribution in the two set-ups. For SPECT, four different radioisotopes are used, with energies lying between 73 to 511 keV. The dose rate distribution for different thickness of lead wall at a number of distances from the source is plotted and the results are analyzed and discussed. The distance considered safe for each source was found to be less than 45 cm without any lead wall. For CT, the geometry was kept identical but using X-rays of a W anode Roentgen tube as source. It is seen that the safe distance for radiation workers is 7512 cm in case of 0 cm Pb wall. The introduction of 0.5 cm Pb wall lowers the safe distance by ~ 96.83%. Attenuation percentages for both SPECT and CT are also discussed.

Introduction

Each new technology, specifically mention those related to health and medicine, before putting it into operation requires a large number of tests and trials that ensure that when used they are as harmless as possible to man. This refers to both the patient and the staff that uses it.

All these tests are carried out from the moment the technique is conceived, while the construction work is being carried out, and after completion before being exploited. Especially important are those diagnostic and medical treatment techniques that use ionizing radiation, which can be from simple and common X-ray equipment to sophisticated gamma cameras or PET and SPECT scanners.

In the present work, the distribution of the dose rate for different sources in the vicinity of a preclinical SPECT/CT hybrid scanner system with the distance is calculated, with the use of mathematical simulation.

The main objective is to determine the working distance considered safe for the occupationally exposed personnel. The simulation system codes GEANT4 and MCNPX, based on Monte Carlo method, were used.

Materials and Methods

(i) Computed Tomography (CT)

Computed tomography (CT) scanning, also known as, especially in the older literature and textbooks, **computerized axial tomography (CAT)** scanning, is a diagnostic imaging procedure that uses x-rays to build cross-sectional images ("slices") of the body [1]. Cross-sections are reconstructed from measurements of attenuation coefficients of x-ray beams in the volume of the object studied.

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. Using this principle, CT allows the reconstruction of the density of the body, by two-dimensional section perpendicular to the axis of the acquisition system.

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 emitter 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). Figure 1 shows a clinical CT scanner where the bed for the patient is seen in the foreground, and behind it the toroidal construction where the X-ray source, the detector and all the control mechanics and electronics are included.

In order to obtain tomographic images of the patient from the data in "raw" scan, the computer uses complex mathematical algorithms for image reconstruction. A tomographic image of a part of the human body obtained using a CT scanner is presented in figure 2.

Fig.1: CT Scanner (Case courtesy of Wikipedia, Radiopaedia.org, rID: 55278).

Fig.2: Fractures as seen on a CT scan.

Source: James Heilman, M.D., [CC-BY-SA-3.0].

(ii) Single photon emission computed tomography (SPECT)

Single photon emission computed tomography (SPECT) is a form of non-invasive nuclear imaging used in order to determine how organs inside the body work [2]. The scan can be used to illustrate how, for example, the blood flows into the heart and chemical reactions that are happening in the body.

SPECT scanning is similar to positron emission tomography (PET), as both use the injection of a radioactive tracer; for the SPECT scan, the tracer remains in the patient's bloodstream. There are three main tracers used in SPECT imaging: technetium-99m, iodine-123 and iodine-131. The radioactive tracer then emits gamma rays (a form of electromagnetic radiation), from the patient; which contrasts with the PET scans which emit positrons.

These rays are then detected by the gamma camera which rotates through 360 degrees around the patient. This rotation around the patient enables the cross-sectional images to be assembled three-dimensionally as in computed tomography. In figure 3 is shown an example of clinical SPECT scanner. This means that the resulting images are able to be viewed either as a three-dimensional entity or as a series of thin slices through the subject, as is presented in figure 4.

Fig.3: A SPECT Scanner.

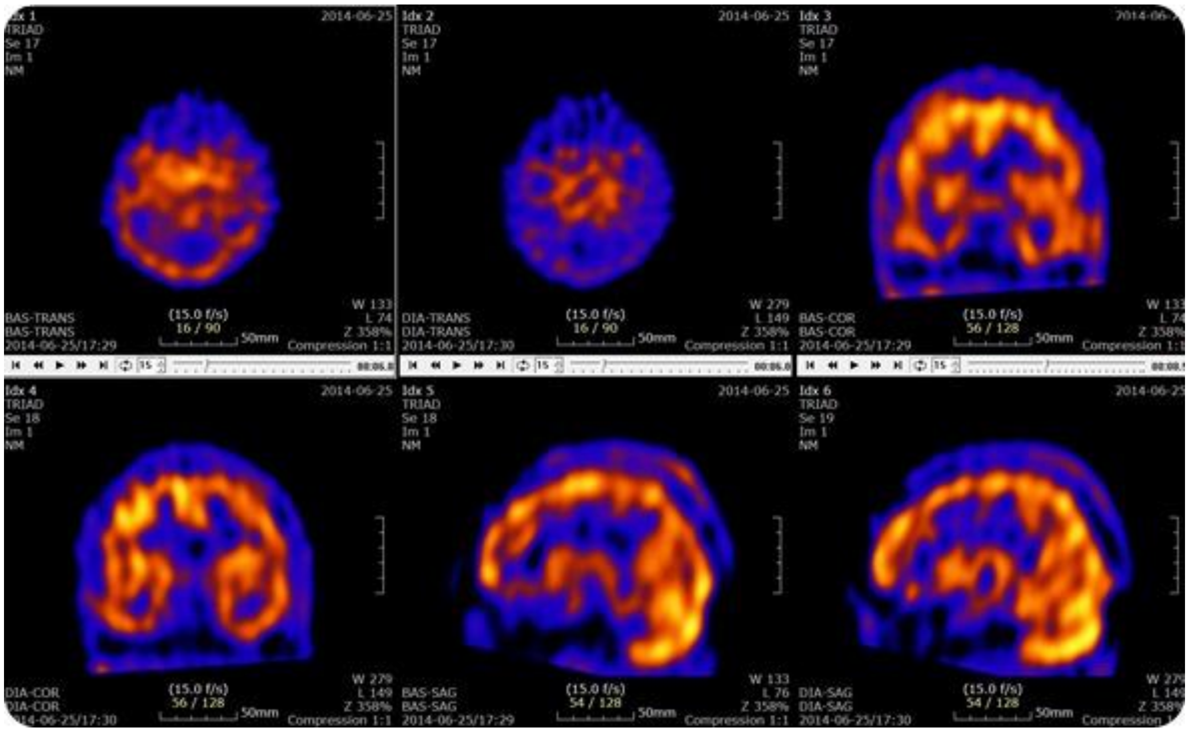

Fig.4: Brain SPECT with Acetazolamide Slices.

A preclinical scanner bases its principles on the same as the clinical scanners discussed here, with the difference that in preclinical ones the dimensions are usually more compact, and the doses are lower. This is because they use as biological targets not humans, but laboratory animals such as mice, rats, rabbits and others.

GEANT4 and MCNPX code systems

Generally speaking, the Monte Carlo method provides a numerical solution to a problem that can be described as a temporal evolution ("translation/reflection/mutation") of objects ("quantum particles" [photons, electrons, neutrons, protons, charged nuclei, atoms, and molecules], in the case of medical physics) interacting with other objects based upon object-object interaction relationships ("cross sections"). Mimicking nature, the rules of interaction are processed randomly and repeatedly, until numerical results converge usefully to estimated means, moments, and their variances. Monte Carlo represents an attempt to model nature through direct simulation of the essential dynamics of the system in question. In this sense, the Monte Carlo method is, in principle, simple in its approach—a solution to a macroscopic system through simulation of its microscopic interactions [3]. Therein is the advantage of this method. All interactions are microscopic in nature. The geometry of the environment, so critical in the development of macroscopic solutions, plays little role except to define the local environment of objects interacting at a given place at a given time.

Monte Carlo codes are widely used in simulations due to the stochastic behaviour of radiation and particles in matter.

The Geant4 (**Ge**ometry **an**d **t**racking version **4**) is very popular nowadays due to its completeness in terms of toolkit [4]. It can simulate all the practically possible particles by making use of various physical processes that it includes in its package.

Geant4 is a simulation toolkit for the transport of particles through matter. It finds its application in a number of fields. These include high energy physics and nuclear experiments, medical, accelerator and space physics' studies. Geant4 is the successor of **Geant3**, the world standard toolkit for HEP detector simulation. Geant3 was based on Fortran, thus had limitations. Geant4 is implemented in the C++ programming language. Geant4 caters to the complete physical simulation. These include detector construction, neutron transport and tracking, etc. One needs to choose different physics models in accordance with the physical phenomenon involved in the interaction.

In figure 5, a representation is shown wherein an isotropic point sized gamma source is kept at a distance from a detector material (in red). The green lines represent gamma rays in the figure.

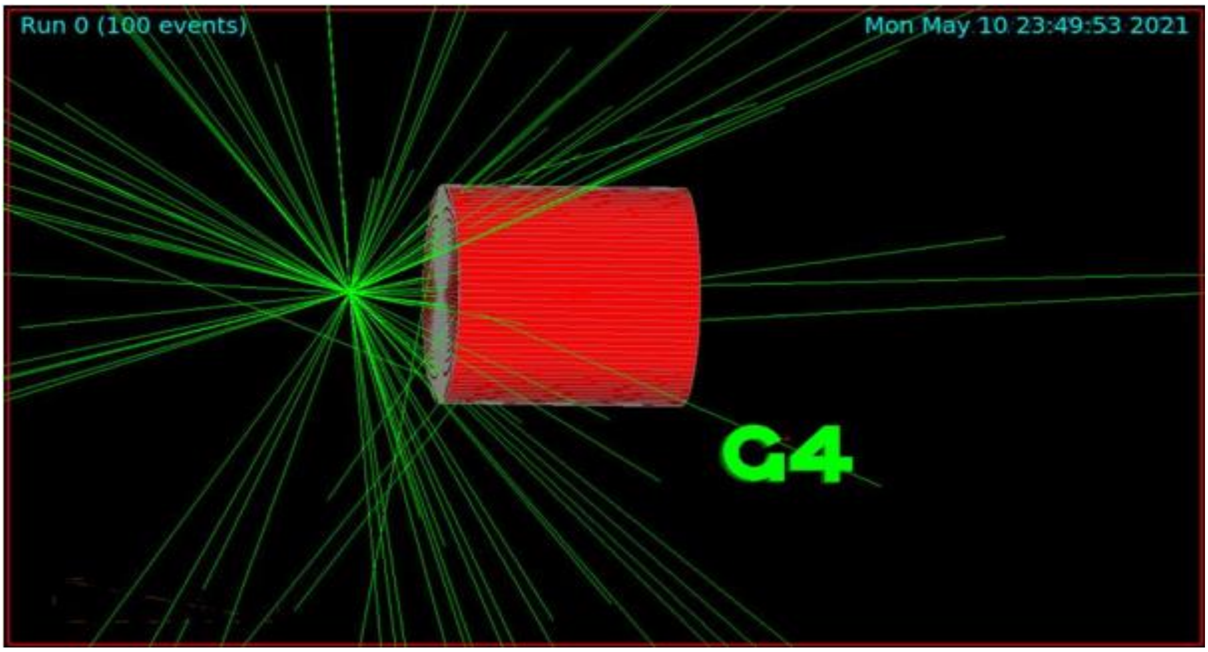

Fig.5: A visual representation of detector geometry and particles in Geant4.

The **MCNPX** is a 3D code consisting of a group of subroutines for sequential simulation by the Monte Carlo Method [5] of the individual probabilistic events that make up the transport processes of 34 types of different particles and photons, in a geometric configuration given three-dimensional and with a varied composition of materials. This software has many applications some include radiological protection and dosimetry, radiological shielding, radiography, medical physics, nuclear criticality safety, detector design and analysis, etc.

Written in Fortran, it is fundamentally based on the use of the effective section of each type of interaction and the statistical nature of the transport process to predict the probability of distribution of specific parameters such as energy losses and angular detection.

To interact with the code, the user must create a file (input file) with all the information required to perform the simulation. The MCNPX input file contains the specifications of the materials that will be involved in the interaction process, the geometry of the experiment, the characteristics of the source and the outputs desired by the user (Tally). During the simulation of the interactions, the program will take into account all the specifications entered by the user in the input file. All the outputs used from the MCNPX are normalized by the number of incident particles from the source (or the number of stories calculated) and are reported together with their estimated relative error.

The results presented were simulated with the MCNPX using a large number of stories (1E7) to achieve adequate statistics.

Sources

For the CT configuration, the W anode X-ray tube was approximated to a point source positioned 1 mm in front of the anode. This source emits only in the phantom direction within a solid angle 20°. The full X-ray tube energy spectrum was considered in the simulation, and it was calculated for a potential difference of 120 keV (figure 6) [6].

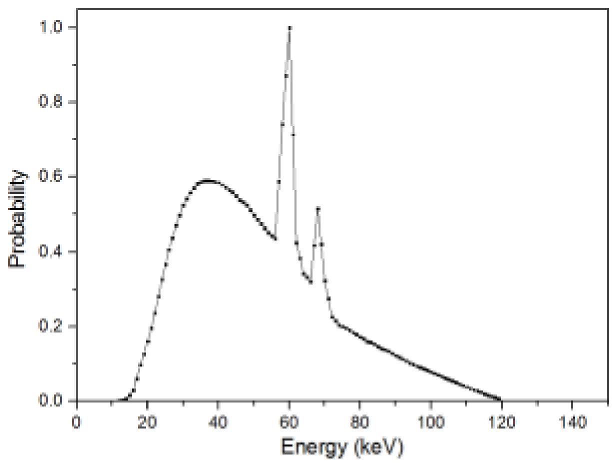

Fig.6: The tungsten anode spectrum with 1 keV intervals.

For SPECT technique, various gamma radioisotopes are used. The gamma radioisotope source, which is injected into the animal under study in the SPECT technique, has been conceived in simulation as a point-like source with photons emitted isotropically. It is positioned in the center of mouse phantom (coordinate center). The energy of the gamma source is selected depending on the isotope to be used, and the activity was taken 10 MBq. The radioisotopes used in the present work are: ^{201}Tl (73 keV), ^{99m}Tc (140.5 keV), ^{131}I (364 keV), and ^{18}F (511 keV).

Dose safe limits

It is important to regulate safe dose levels for both professionals and common people in order to avoid safety and health hazards. The International Commission on Radiological Protection (ICRP) recommends the safe dose limits [7, 8].

The safe limits decided are different for public and the professionals. A whole-body effective dose limit is set at 20 mSv/year or equivalently 2.3 μSv/hour for occupationally exposed employees. See Table 1.

For the conversion of the outputs obtained by the code system from flow units to dose units, were used the coefficients recommended by [9].

Table 1. Dose limits established for radiation workers and public.

	Radiation workers	Public
Effective dose	20 mSv/year	1 mSv/year
Equivalent dose to the lens of the eye	20 mSv/year	15 mSv/year
Equivalent dose to the skin	500 mSv/year	50 mSv/year
Equivalent dose to the hands and feet	500 mSv/year	-

Results

(i) SPECT

Figure 6 shows a simplified SPECT geometry constructed with Geant4. Different constituents in the geometry are labelled in the figure caption. An isotropic point source emitting photons is constructed at the coordinate centre (0,0,0), i.e, at the centre of mouse (red cube). Four different isotopes namely, ^{201}Tl, ^{99m}Tc, ^{131}I, and ^{18}F, of activity 10 MBq are used as photon source. Figure 7 shows a different view of geometry, where GaAs:Cr detector is clearly visible.

Point detectors at different distances along the x-axis were placed using the F5 tally card in MCNPX. The fluence rates were obtained at different distances. The results obtained in units of cm^2 are converted to units of dose, pSv, and then to µSv/h. This conversion is done using the DE and DF cards of the MCNPX.

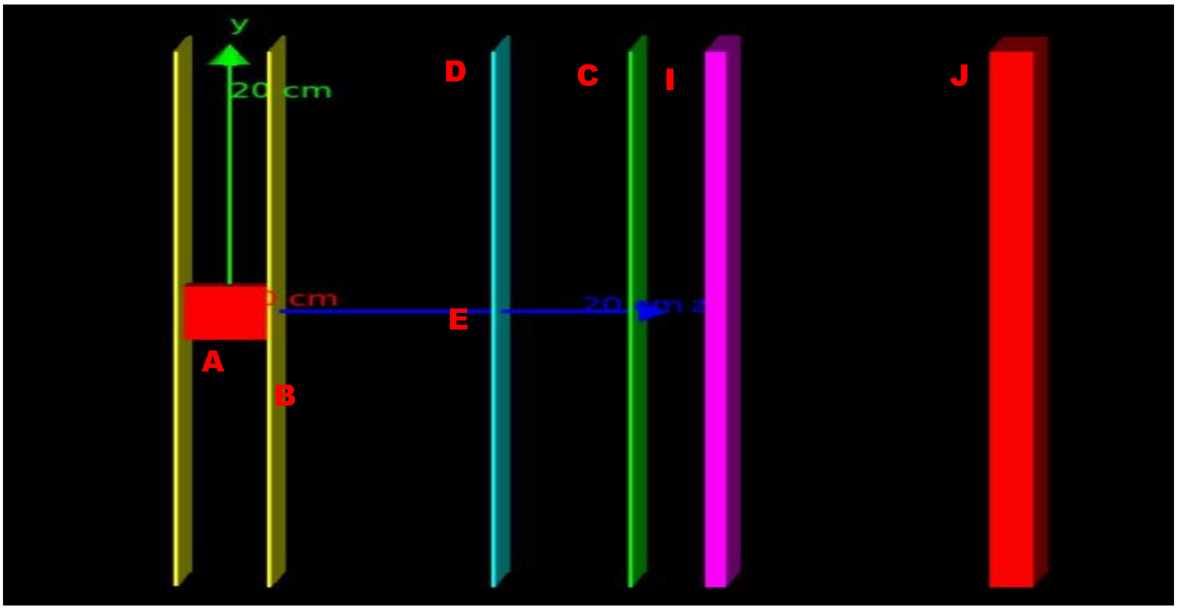

Fig.6: Schematic representation of the SPECT Geometry. Various components here are: A - mouse, B -polypropylene bed, C - stainless 202 protective wall, D – Fiber glass, Type C (PCB) wall (detector support), E – 500 µm GaAs:Cr detector, I – duralumin wall (gantry), J – Pb protective wall.

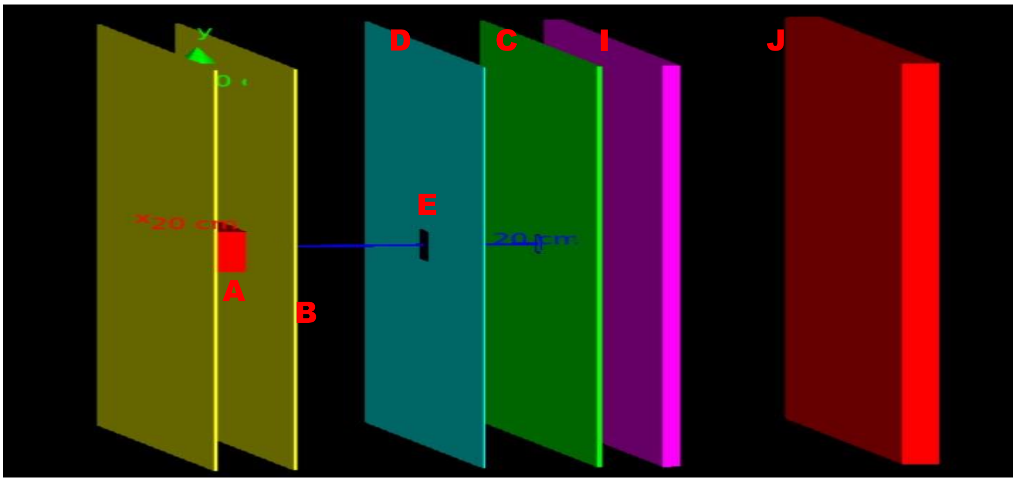

Fig.7: A different view of the geometry, showing GaAs:Cr detector E (small black parallelepiped).

Figures 8-11 show the variations of dose rate as function of distance from the source, for the four gamma sources mentioned above, and for different thicknesses of Pb wall. The orange straight line parallel to x-axis denotes the safe dose level considered for occupationally exposed workers. It is evident from all the graphs that introduction of lead wall (at 35 cm) reduces the dose rate significantly.

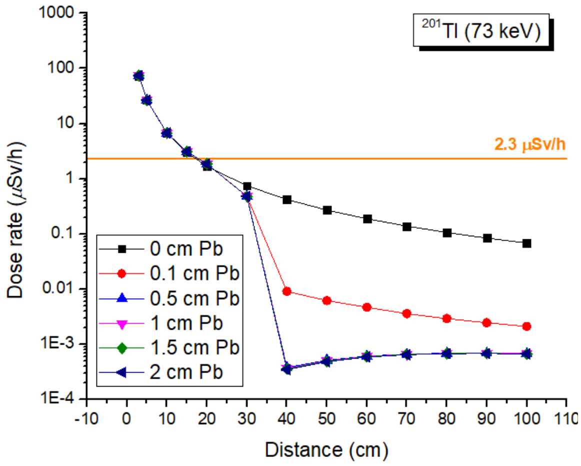

Fig.8: Dose rate vs distance graph for ^{201}Tl.

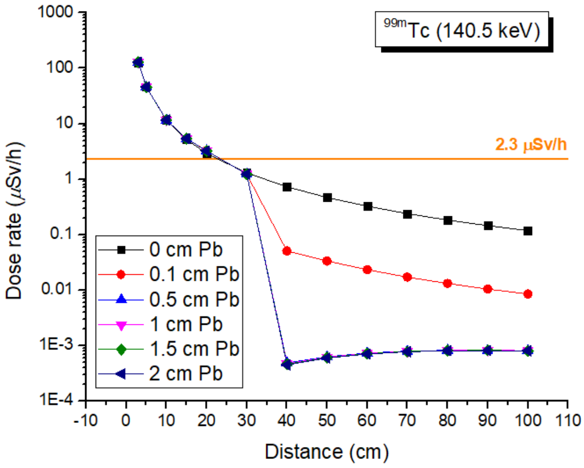

Fig.9: Dose rate vs distance graph for ^{99m}Tc.

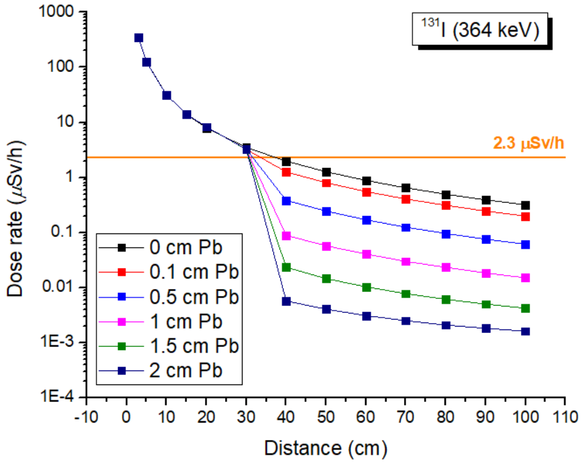

Fig.10: Dose rate vs distance graph for ^{131}I.

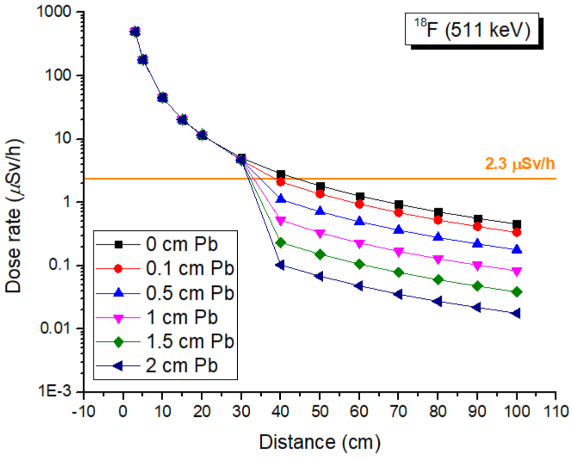

Fig.11: Dose rate vs distance graph for ^{18}F.

From figures 8-11, estimating the attenuation produced by the Pb wall at a distance of 40 cm from the source position, the results presented in table 2 are obtained.

Table 2. Dose rate attenuation produced by Pb wall in % units.

Pb wall thickness (cm)	^{201}Tl	^{99m}Tc	^{131}I	^{18}F
0.1	97.84	93.06	36.53	25.59
0.5	99.90	99.90	80.65	60.94
1	ident	ident	95.50	81.54
1.5	ident	ident	98.81	91.79
2	ident	ident	99.71	96.36

Figure 12 shows the variation of dose rate with distance for all the sources used in case of 0 cm Pb wall. Figure 13 shows the zoom-in of the area where all the curves cross the safe dose level orange line. It is seen that the safe distance for radiation workers without any lead wall is **17.2 cm** in case of ^{201}Tl, **22.7 cm** in case of ^{99m}Tc, **37.2 cm** in case of ^{131}I, and **44.6 cm** in case of ^{18}F.

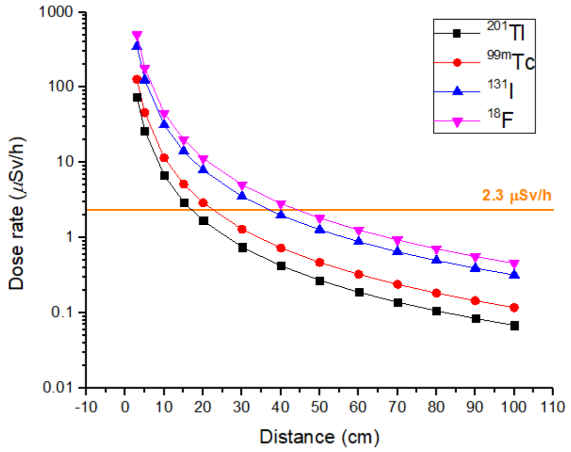

Fig.12: Dose rate vs distance graph for 0 cm Pb wall.

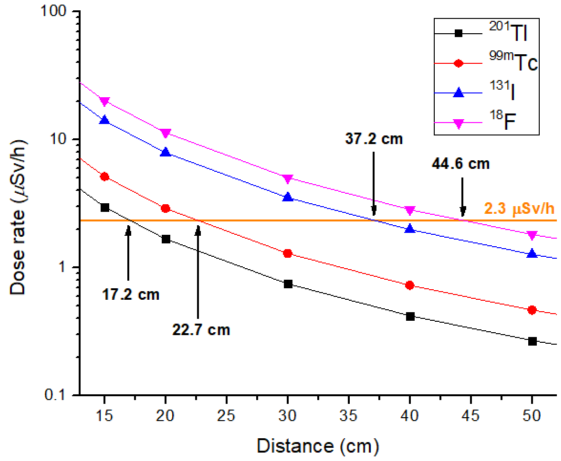

Fig.13: Zoom-in view of the area in concern.

Staying at distances less than the values determined above for each type of radioisotopic source is harmful to the health of the exposed person.

(ii) CT – X-rays

The geometry was kept identical with the one in case of SPECT. The monoenergetic source was removed and an X-ray tube was simulated instead. The X-ray source with W anode was positioned at (-13.6,0,0). The tube was operating at a potential difference of 120 keV and current 350 µA.

Figure 14 shows the variation of dose rate as a function of distance for the case of CT X-rays for different thicknesses of Pb wall. Figure 15 shows the zoomed view of the same graph where the curves cross the safe dose level. It is seen that the safe distance for radiation workers is **7512 cm** in case of 0 cm Pb wall, **1252 cm** in case of 0.1 cm Pb wall, and **238 cm** in case of 0.5 cm and thicker Pb wall. The introduction of 0.5 cm Pb wall lowers the safe distance by ~ **96.83%**.

Estimating the attenuation produced by the Pb wall at a distance of 1500 cm from the source position, we see that there is **98.93%** attenuation by 0.1 cm Pb wall, which brings the dose rate down the safe level. The attenuation for 0.5 cm and greater thicknesses of Pb wall at the same distance is equal to **99.8%**.

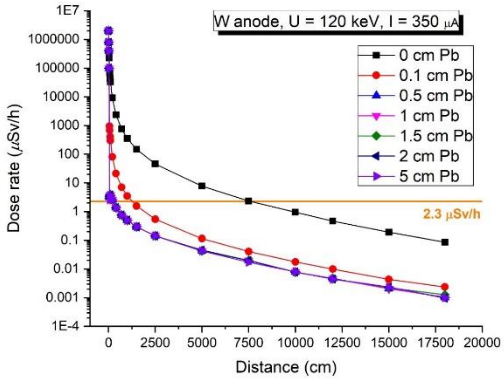

Fig.14: Dose vs distance graph for CT X-rays operating at 120 keV and 350 μA.

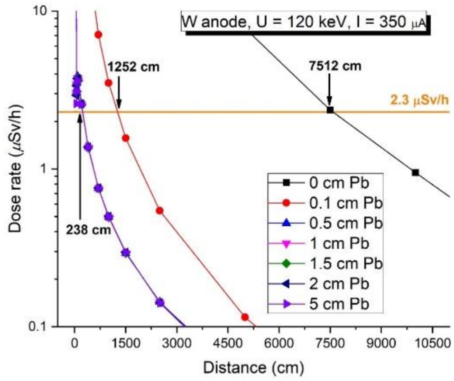

Fig.15: Zoom-in view of the area in concern.

Staying at distances from the source closer than described above can pose serious risks to the health of professionals.

Taking into consideration that the safe distance values determined here for the CT configuration are relatively large, it is always justified, in addition to the protection that the system includes, to use other means of protection for professionally exposed personnel. For example, concrete walls, lead bricks, leaded glass, etc., acting as additional protective barriers, as well as personal protective equipment [10].

Conclusion

MCNPX and Geant4 code systems were used to simulate the passage of radiation and study the dose rate distribution in SPECT and CT scanners. The results were used to determine the minimum distance from the source considered safe for occupationally exposed workers and to determine the attenuation caused by various thicknesses of Pb wall.

For SPECT, it was seen that the value safe distance increases with an increase in the photon's energy. It was estimated that the safe distance for radiation workers without any lead wall was a minimum of 17.2 cm in case of ^{201}Tl and a maximum of 44.6 cm in case of ^{18}F. Thus, the safe distance was lesser than 45 cm for all the sources used. The attenuation produced by Pb wall for different radioisotopes at different thicknesses of Pb wall are determined and discussed in the text.

For CT, it was found that the safe distance for radiation workers is 7512 cm in case of 0 cm Pb wall, 1252 cm in case of 0.1 cm Pb wall, and 238 cm in case of 0.5 cm and thicker Pb wall. The introduction of 0.5 cm Pb wall lowers the safe distance by ~ 96.83%. The attenuation for X-rays produced by the Pb wall at a distance of 1500 cm from the source position, results in **98.93%** for 0.1 cm Pb wall, and **99.8%** for 0.5 cm and greater thicknesses of Pb wall.

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