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

Supervisor:
Dr. Antonio Leyva Fabelo

Student:
Bhavika
Indian Institute of Technology
Roorkee, India
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Contents

Abstract

Nowadays it is estimated that 50% of the population exposure to radiation comes from medical sources. That's why the minimization of the received dose by both the patients and the operators of the different technologies that use radioactive sources has become a world-wide concern. The objective of the present work is to determine minimum distances considered safe for the personnel occupationally exposed to radiation, from the radiation sources used in preclinical SPECT/CT scanners, and to see the effect of lead wall thickness on these values. MCNPX code is used for simulating the passage of radiation and to study the dose rate distribution in the two set-ups. For SPECT, ^{99m}Tc radioisotope is used as source. 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. For CT, the geometry was kept identical but using X-rays of a W anode Roentgen tube as source. The procedure used was the same.

1. 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 to ensure that when used they are as harmless as possible to man. This refers to both the patient and the staff wo use 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 with the distance of the dose rate for different sources in the vicinity of a preclinical SPECT/CT hybrid scanner system is calculated, using for this the mathematical simulation.

The main objective is to determine the working distance considered safe for occupationally exposed personnel. The based-on Monte Carlo method code systems MCNPX used for this.

2. Materials and Methods

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]. These slices are called tomographic images and contain more detailed information than conventional X-rays. Several successive slices are collected by the machine's computer, they can be digitally stacked together to form a three-dimensional image of the patient that allows for easier identification and location of basic structures as well as possible tumors or abnormalities

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. 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.

Figure 1. CT scanner [2].

Figure 2. Fractures as seen on a CT scan [3].

Figure 3. A SPECT Scanner [4].

The SPECT tomography is a 3D nuclear medicine tomographic imaging technique using gamma rays [5]. The technique requires delivery of a gamma-emitting radioisotope into the patient, usually through injection into the bloodstream. There are three main tracers used in SPECT imaging: Technetium-99m, Iodine-123 and Iodine-131. The radioisotope is usually linked to a certain molecule, which is chosen according to its affinity with the organ to be studied, and where it will preferentially accumulate. The radioactive tracer then emits gamma rays from the patient; in contrast with the PET scans, that emit positrons. These rays are then detected by the gamma camera, rotating 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.

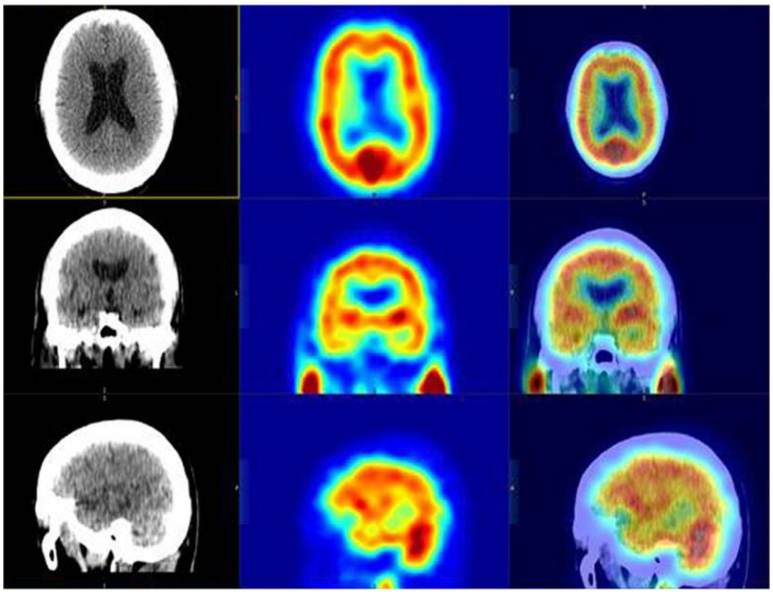

Figure 4. Brain SPECT with Acetazolamide Slices [6].

3. MCNPX code system

MCNPX, which stands for Monte Carlo N-Particle eXtended, developed and maintained by Los Alamos National Laboratory, is a general-purpose Monte Carlo radiation transport code for modeling the interaction of radiation with matter.

The use of the Monte Carlo method in nuclear medicine calculations has increased almost exponentially in the last decades.

The MCNPX is a 3D code consisting of a group of subroutines for sequential simulation by the Monte Carlo Method **[7]** 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.

MCNPX is very versatile and easy to use. Includes a powerful general source, criticality source, and surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data. The key value MCNPX provides is a predictive capability that can replace expensive or impossible-to-perform experiments.

To interact with the code, the user must create an 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. 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.

In current work MCNPX code systems were used to simulate the transport of X-rays, gamma and electrons in a SPECT-CT scanner in order to determine the distribution of the dose rate, for each geometric configuration separately, and for different thickness values of the Pb protection wall **[12]**.

The MCNPX tally F5 for obtaining the particle fluency at selected position, and the cards DE, DF and FM for converting the F5 results to dose rate units, are used.

In order to obtain a good statistic, 10^7 source histories were employed.

4. 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 **[8, 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	-

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 as shown in 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 [10]. A group of point detectors were placed in the MCNPX input file at different distances from the source, and with them the particle fluency distribution was measured. The results obtained in units of cm^{-2} are converted to units of dose, pSv, and then to µSv/h.

4.1. Dose rate calculations in SPECT-CT system

For the evaluation of the dose rate distribution at different points around the SPECT-CT system, some geometric considerations were taken into account.
In the case of SPECT configuration, a point source with photons isotropic emission was considered. It is positioned in the center of mouse phantom, inside of a sphere simulating the heart and emitting with energy 140 keV (^{99m}Tc). The activity of the source is 10 MBq.
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 20° solid angle. The full X-ray tube energy spectrum was considered in the simulation and it was calculated using interpolating polynomials (TASMIP) for 120 keV as shown in figure 6 [11].

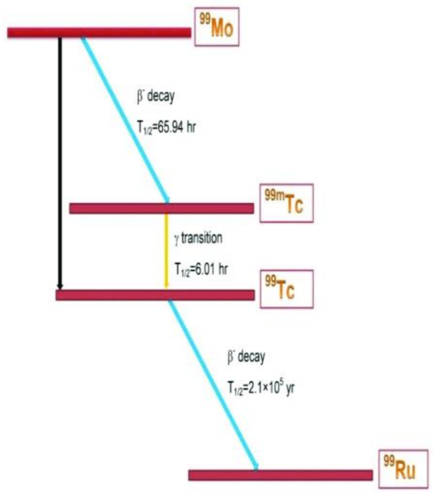

Figure 5. Decay scheme of ^{99}Mo.

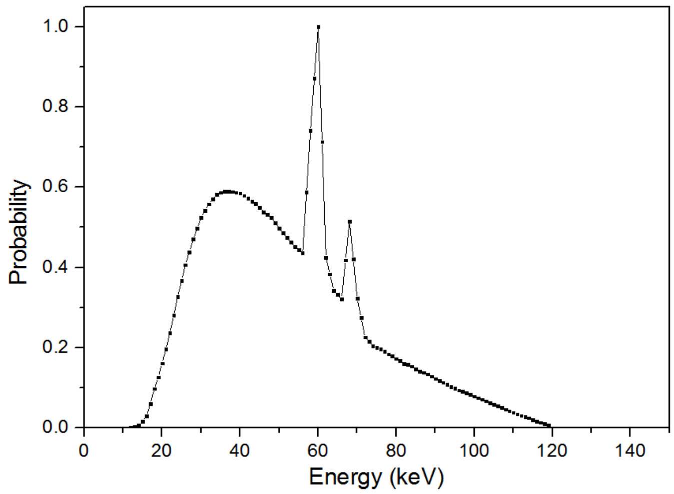

Figure 6. The tungsten anode X-ray spectrum with 1 keV intervals.

5. Results

The simulations were performed independently for both the techniques contemplated in SPECT/CT using MCNPX code. The results obtained for each of them will be presented.

5.1. SPECT

Figure 7 shows the 2D geometric arrangement used for the determination of the dose rate dependence with the distance from the source with the help of point detectors. In figure different components are shown and identified. The photon source ^{99m}Tc is positioned at the coordinate (0, 0, 0). The point detectors were located on the x-axis to the right of zero at a distance 1.85 cm, 5 cm, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm, 100 cm as shown in the figure 8.

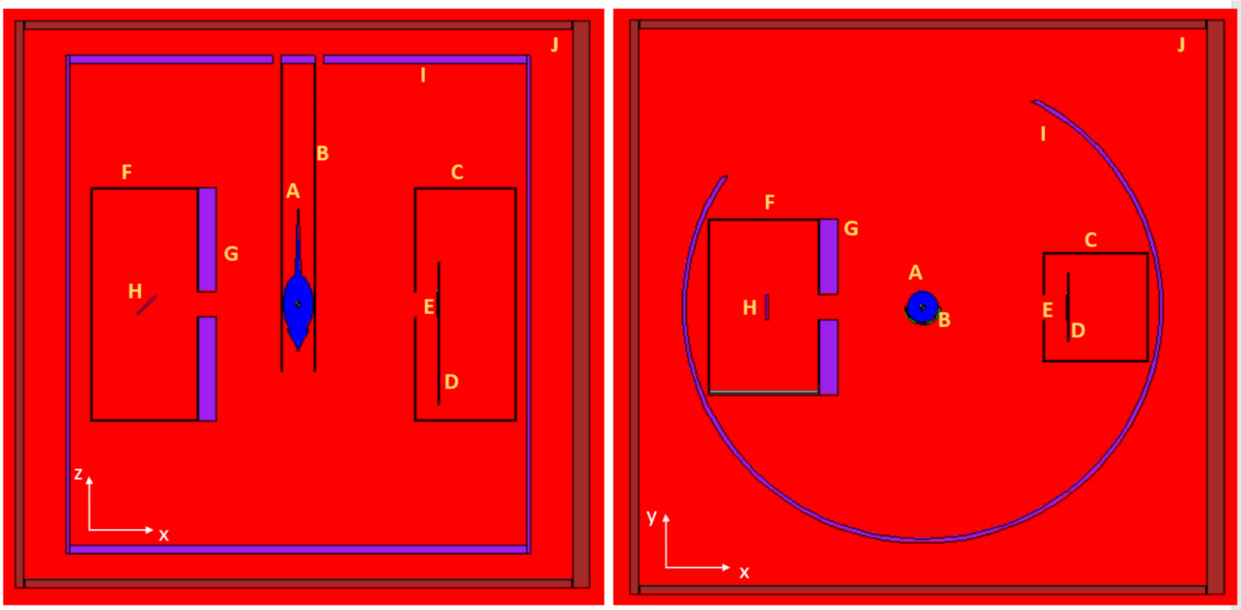

Figure 7. Schematic representation of the geometric arrangement considered in the calculations; (a) - view in the xz plane, and (b) - view in the xy plane. A - mouse, B - polypropylene bed, C - stainless 202 protective case for detector, D - fiberglass detector support, Type C (PCB), E - 1 mm thick CdTe detector, F - stainless 202 protective case for X-ray tube, G - duralumin protective plate, H - W anode of X-ray tube, I - gantry cylinder, J - Pb protection walls.

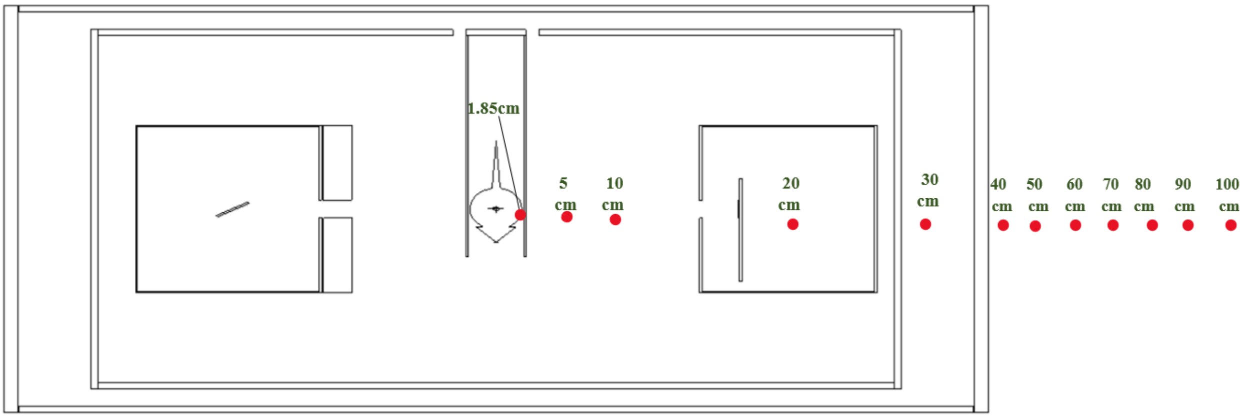

Figure 8. Red dots represent here the point detectors that are located on the x-axis at different distances right to zero.

Here the figure 9 shows some of the 3D images of SPECT/CT arrangement which are obtained using 3D dynamic plotting from the menu of Vised X_22S. In 3D dynamic plotting, user can input the cell number in which they are interested and they want to display. To track the particle "plot particle track" was used from the menu and we get the figure 10 where the source is placed at the center of mouse, green line indicates the photons, and blue line indicates the secondary electron.

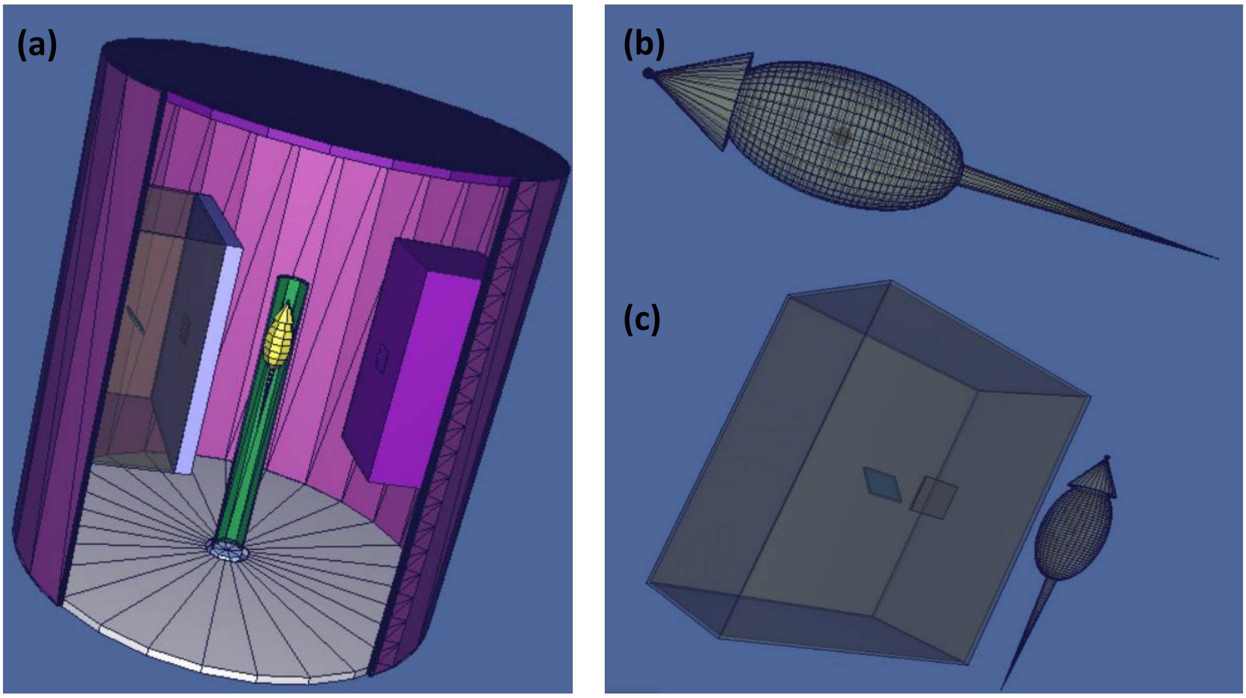

Figure 9. 3D images of the (a) SPECT/CT arrangement obtained with the VisedX_22S, (b) mouse, (c) mouse shown next to the 202 stainless steel box where the X-ray bulb is located (the box window and the X-ray W anode are also seen).

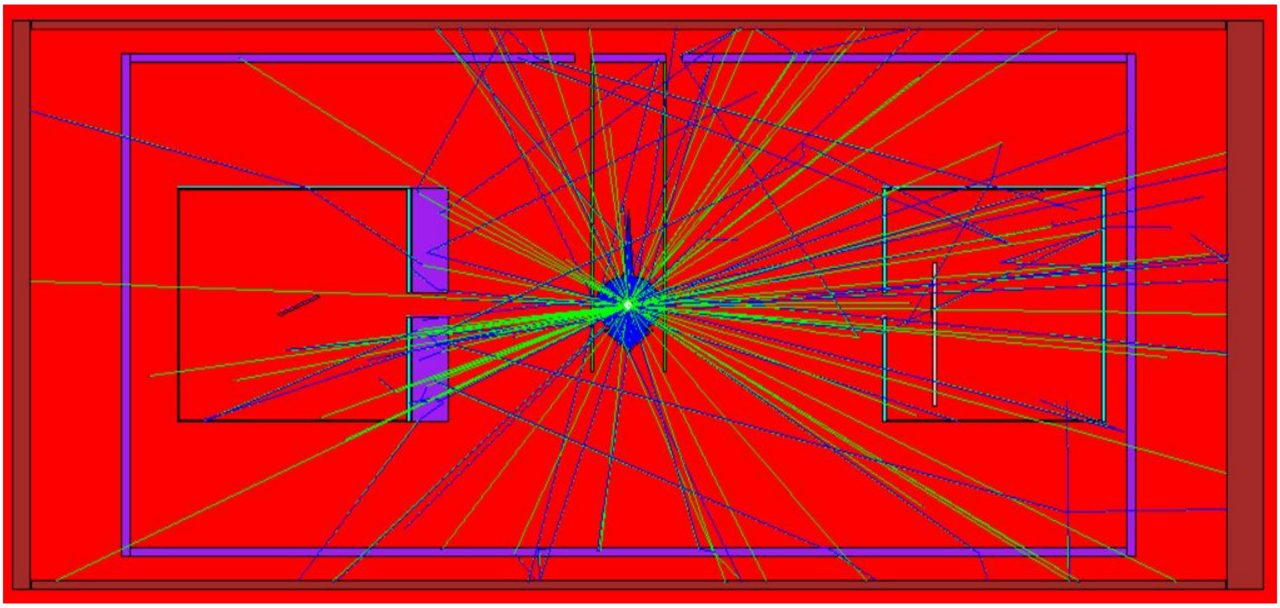

Figure 10. Illustration of the tracks for photons (green lines) and secondary electrons (blue lines) for SPECT/CT system with ^{99m}Tc source.

Figures 11 shows the variations of dose rate as function of distance from the source, for eight 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. Here the figure 11 shows that Pb walls are not necessary to use in the SPECT arrangement, as the safe value of dose reaches at 20 cm from the ^{99m}Tc placed at origin.

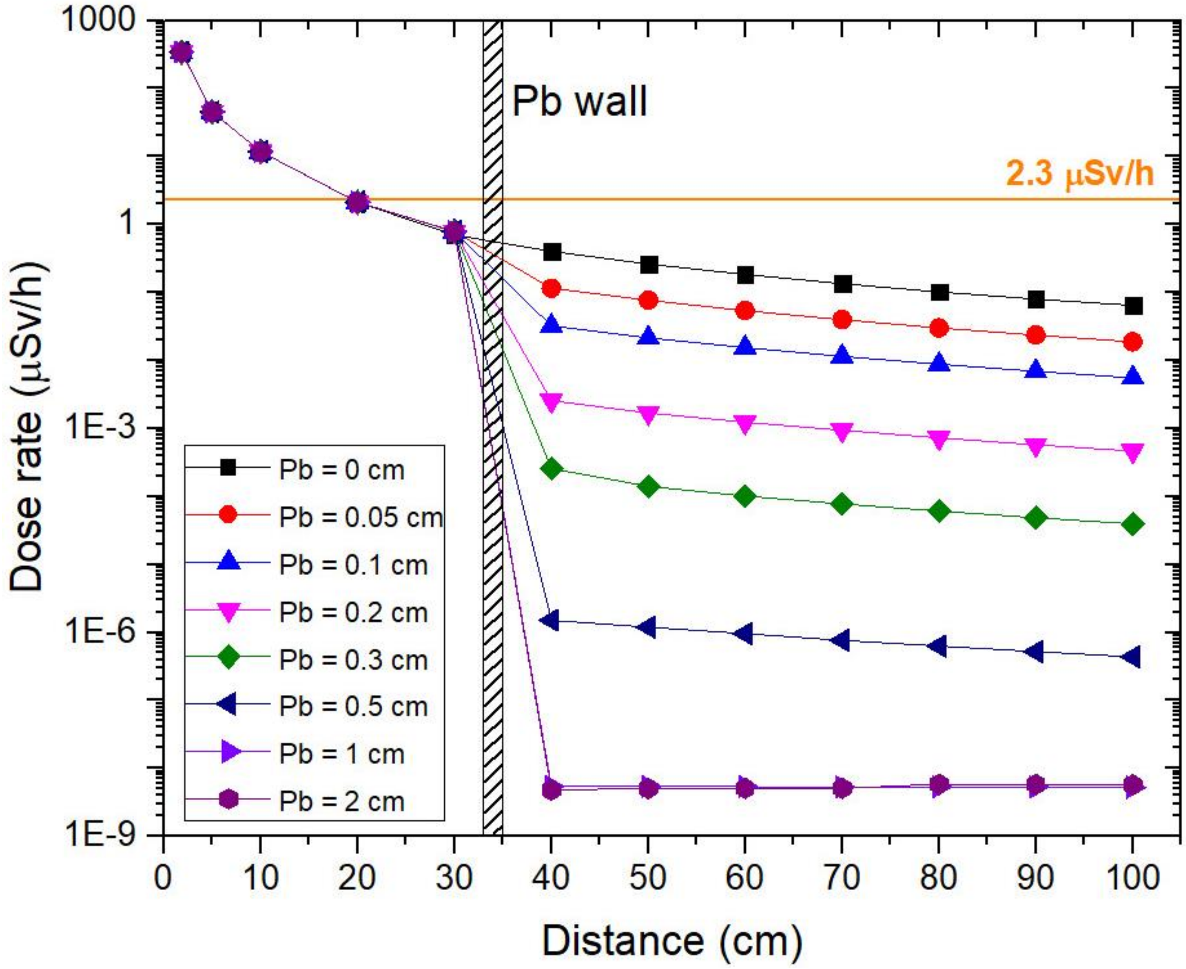

Figure 11. Dose rate vs. distance behavior calculated for ^{99m}Tc source for eight different geometric conditions.

5.2 CT

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 (-18,0,0), and it emits in the direction of the mouse and within a solid 20-degree cone. The tube was operating at a potential difference of 120 keV and current 350 μA.
Figure 12 shows the point detectors placed on the x-axis to the right of zero at a distance 1.85 cm, 5 cm, 10 cm, 20 cm, 30 cm, 40 cm, 100 cm, 200 cm, 500 cm, 1000 cm, 2000 cm, 5000 cm, 8000 cm, 11000 cm, 15000 cm. Figure 13 shows the visual illustration of the track of particles with the help of VisedX_22S.
Figure 13 shows the visual description of tracking of particles. Here the X-ray source is placed at point **H**, that emits radiations in the direction of the mouse and within solid angle 20° cone. And here green line indicates the photons and blue lines indicates the secondary electrons.

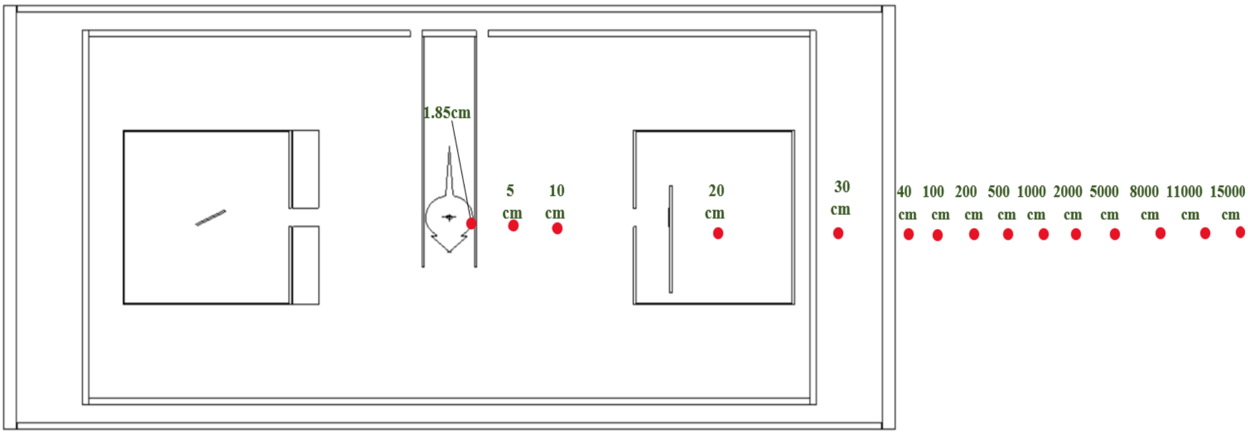

Figure 12. Red dots represent here the point detectors that are located on the x-axis at different distances right to zero.

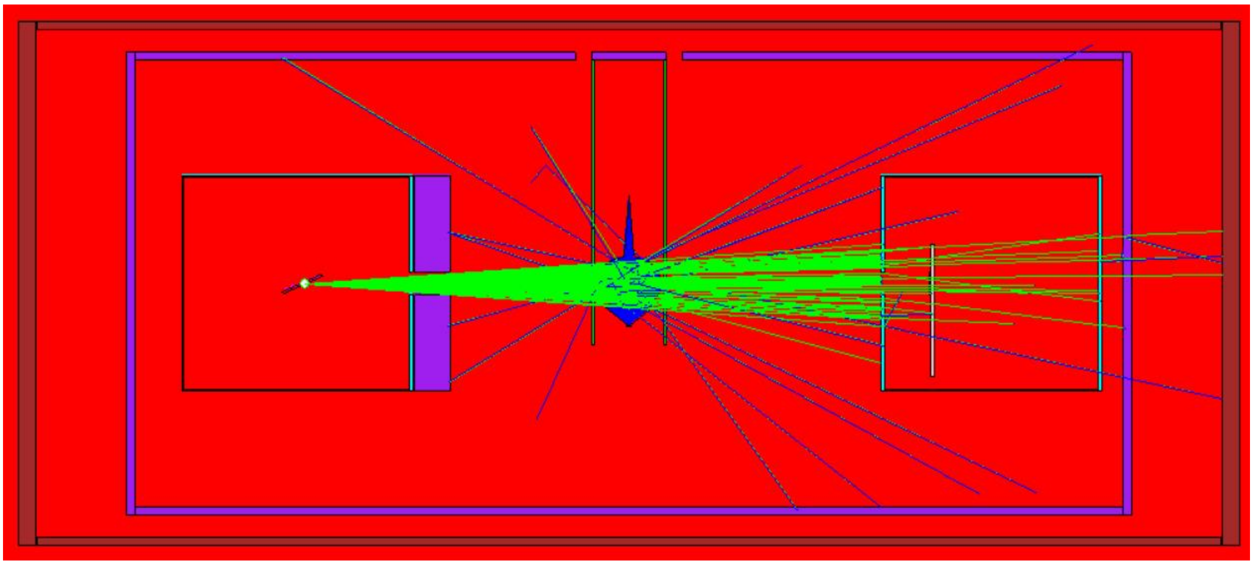

Figure 13. Illustration of the tracks for photons (green lines) and secondary electrons (blue lines) for SPECT/CT system in the case of X-ray tube sources.

Figure 14 shows the variation of dose rate as a function of distance for the case of CT 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 **3545 cm** in case of 0 cm Pb wall, **2932 cm** in case of 0.01 cm Pb wall, **1440 cm** in case of 0.05 cm Pb wall, **715 cm** in case of 0.1 cm Pb wall, **75 cm** in case of 0.3 cm Pb wall, **38 cm** in case of 0.5 cm Pb wall, **34 cm** in case of 1 cm Pb wall, **32 cm** in case of 2 cm Pb wall. Staying at distances from the source closer than described above can pose serious risks to the health of professionals. The introduction of lead wall greater than or equal to thickness 0.5 cm brings the dose rate down the safe level. With this shielding wall (Pb) of thickness greater than or equal to 0.5 cm, it is possible to reduce safe distance by ~ **99.01%.**

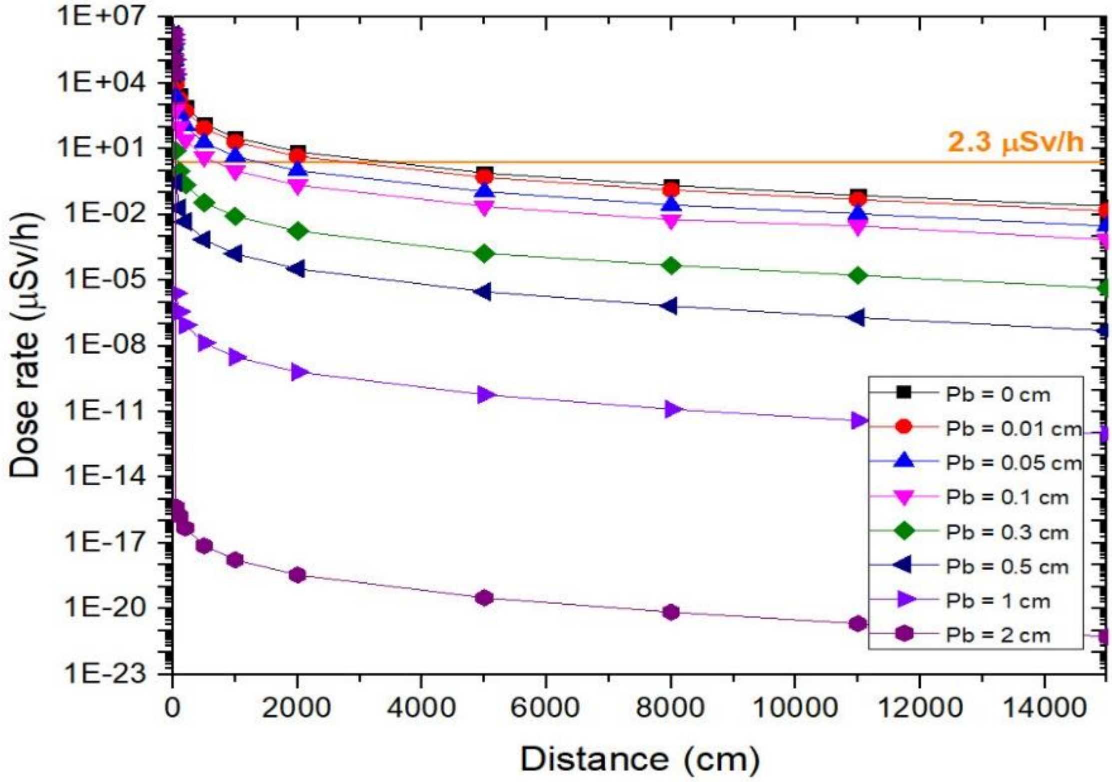

Figure 14.. Dose vs distance graph for CT operating at 120 keV and 350 µA.

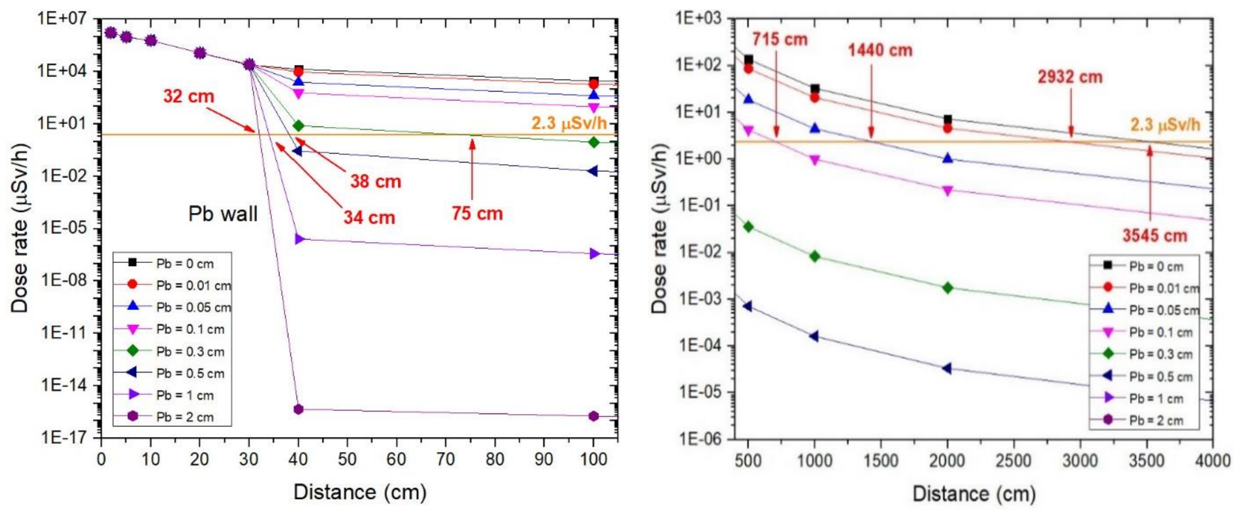

Figure 15. Zoom-in views of areas in concern: (a) - distances closer to the source, (b) - distances further away from the source.

We have seen the great difference, in terms of dose values, that exists between the two techniques that make up SPECT/CT. In the case of the CT arrangement, safe distances determined here are relatively large, and therefore we consider that it is fully justified, in addition to the protection included in the CT system itself, to use other means of protection for professionally exposed personnel. For example, concrete walls, lead bricks, leaded glass, aprons and special glasses, etc., which act as additional protective barriers.

6. Conclusion

Using the MCNPX code system for the simulation of radiation transport in materials, the dose rate distribution has been studied in a preclinical SPECT/CT scanner prototype. Two typical sources used in these devices were taken into consideration, as well as several geometric configurations, in order to determine for each, the smallest distance to the center of the equipment that can be considered safe for occupationally exposed personnel.

For SPECT, it was seen that at 20 cm from the source, the dose rate falls down to the safe limit. Pb wall is at 35 cm and it helps in significantly reducing the dose rate but, according to obtained results it is not necessary to use the Pb wall in the SPECT arrangement.

For CT, Pb wall is playing a major role. The introduction of lead wall greater than or equal to thickness 0.5 cm brings the dose rate down the safe level. It is seen that the safe distance for radiation workers is 3545 cm in case of 0 cm Pb wall, 2932 cm in case of 0.01 cm Pb wall, 1440 cm in case of 0.05 cm Pb wall, 715 cm in case of 0.1 cm Pb wall, 75 cm in case of 0.3 cm Pb wall, 38 cm in case of 0.5 cm Pb wall, 34 cm in case of 1 cm Pb wall, 32 cm in case of 2 cm Pb wall. With this shielding wall (Pb) of thickness greater than or equal to 0.5 cm, it is possible to reduce safe distance by ~ 99.01%.

The use of additional protective barriers for the protection of the personnel involved in its exploitation is highly recommended in the case of the CT scanner.

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