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FINAL REPORT ON THE INTEREST PROGRAMME

Calculation of radiation shielding in a SPECT-CT scanner prototype using based on Monte Carlo code systems

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Abstract

Ionizing radiation is simultaneously an instrument at the service of humanity and a harmful factor that forces us to take measures to prevent dangers and negative effects. Nuclear medicine is one of the areas where radiation protection is vital for both technical personnel and the public. With this premise in mind, the present work is oriented to calculate, by means of mathematical simulation, the dose rate distribution in the vicinity of an experimental arrangement type SPECT/CT scanner, and from these results determine the distances considered safe for occupationally exposed personnel. The simulations were performed independently for the SPECT and CT setups. For SPECT, the simulation was carried out for different radiosotopes in an energy range from 73 to 511 keV, verifying that with increasing photon energy the distance considered safe grows, but it was always less than 45 cm. When different walls are introduced in the studied geometry it was found that although polypropylene bed and the duralumin gantry have an almost imperceptible effect, the addition of the Pb shielding wall constitutes a strong barrier to the passage of radiation from ^{99m}Tc, decreasing the values of the dose rate in 95% - 99%. For the CT configuration, the use of the X-ray tube leads to a dramatic increase in the distance considered safe for occupationally exposed personnel. In the case of the simplest geometry this distance is 9800 cm, but introducing the proposed walls it is obtained that the distance considered safe falls to 420 cm regardless of the thickness of the wall of P in the studied interval; which represents a decrease in the distance of interest of ~ 96%.

Introduction

Radiation protection is a task of the utmost importance in any facility where ionizing radiation is used in order to guarantee the safety of people, animals and the environment. The use of nuclear methods and technologies is increasing in the world, so ensuring effective radiation protection is becoming more important. In the health sector, for example, there are many methods and techniques for diagnosis and treatment that include radioactive sources, accelerators, etc. Ensuring the safety of patients and occupationally exposed workers is vital.

Among the nuclear diagnostic techniques that have become common in any hospital, polyclinic or clinic, a wide list of equipment can be mentioned, from a common X-ray equipment to the most sophisticated gamma cameras, CT, PET and SPECT scanners, figures 1 and 2. Every one of these use ionizing radiation, some even use two or more types of radioactive sources [1].

In the studies focused on the determination of the most optimal and safe radiological conditions for the exploitation of these systems, the mathematical modeling of radiation transport plays an important role. This is because, with its use, it is possible to carry out the simulation experiments in the most realistic way possible and allows to calculate with great precision, not only the doses distribution, but also some hard to measure parameters, quickly and economically [2, 3].

Figure 1. X-ray machine with its operator protected behind a lead-lined glass window.

Figure 2. CT scanner viewed from behind a leaded glass for personal protection.

This work aims to perform the calculation, using the Monte Carlo based code system MCNPX, of the dose rate distribution with distance for different geometries and sources in a SPECT/CT type preclinical scanner. With these results we intend to determine for each case the distance considered safe for occupationally exposed personnel.

Materials and Methods

Computed tomography (CT)

CT scanning is a diagnostic imaging procedure that uses X-rays to build cross-sectional images ("slices") of the body [4]. These 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.

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).

In order to obtain tomographic images of the patient from the data in "raw" scan, the computer uses complex mathematical algorithms for image reconstruction.

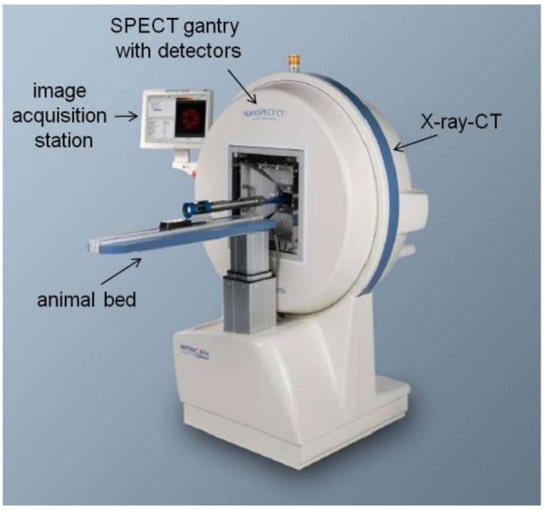
Single photon emission computed tomography (SPECT)

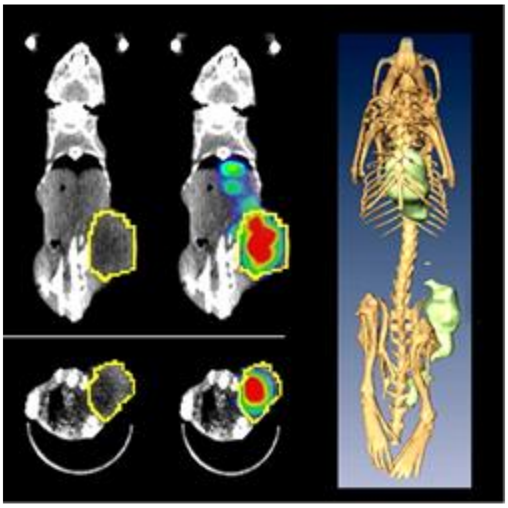
SPECT is a three-dimensional nuclear medicine imaging technique combining the information gained from scintigraphy with that of computed tomography. This allows the distribution of the radionuclide to be displayed in a three-dimensional manner offering better detail, contrast and spatial information than planar nuclear imaging alone.

SPECT machines combine an array of detectors which rotate around the patient on a gantry providing spatial information on the distribution of the radionuclide within tissues. The use of multiple gamma detectors increases the efficiency and spatial resolution. The projection data obtained from the detectors are then reconstructed into three-dimensional images usually in axial slices [5, 6].

SPECT-CT tomography

SPECT scanner may be also combined with CT machine in a form of hybrid imaging: SPECT/CT, a new paradigm in obtaining medical and scientific images able to merge the acquired anatomical information with the functional. Figure 3 (a) shows a SPECT/CT hybrid preclinical scanner, and next to it, figure 3 (b) presents an example of a set of images obtained with this sophisticated device. The SPCT/CT combination has many advantages reported in the literature, for example in [7-9].





(a) (b)

Figure 3. Illustrative image of SPECT/CT tomography system (a), and example of images obtained in this advanced device (b).

Sources

The source of X-ray in CT tomography systems is Roentgen tube (schema in figure 4). In simulations, for the CT configuration, the W anode in the X-ray tube was approximated to a point-like source positioned 1 mm in front of a hypothetical tungsten 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 using interpolating polynomials (TASMIP) for 120 keV [10].

a

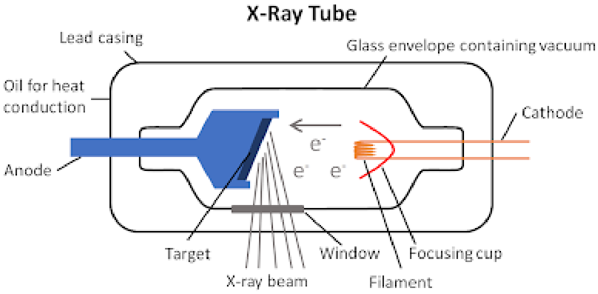


Figure 4. Production of X-Rays in a Roentgen tube.

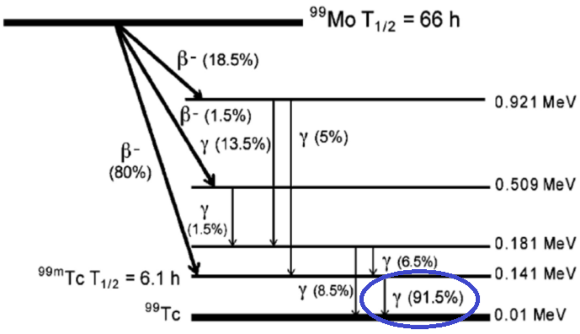


Figure 5. Molybdenum decay.

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. Figure 5, as an example, shows the decay scheme of ^{99}Mo, the precursor of ^{99m}Te.

Dose limits

Dose limits are recommended by the International Commission on Radiological Protection (ICRP). They are in place to ensure that individuals are not exposed to an unnecessarily high amount of ionizing radiation. Dose limits are a fundamental component of radiation protection, and breaching these limits is against radiation regulation in most countries.

The limits are split into two groups, the public, and occupationally-exposed workers [11, 12]. The dose limit for workers proposed by the ICRP was established as an annual effective dose. As presented in Table 1, an effective dose limit of **20 mSv/year** has been set for persons employed in radiation work.

Table 1. Dose limits established for occupationally-exposed workers and public.

	Effective dose	**Equivalent dose to the lens of the eye**	**Equivalent dose to the skin** (averaged over 1 cm^2)	**Equivalent dose to the hands and feet**
Occupationally exposed workers	20 mSv a year, averaged over defined periods of 5 years with no single year >50 mSv	20 mSv a year, averaged over defined periods of 5 years with no single year >50 mSv [2]	500 mSv a year	500 mSv a year
Public	1 mSv a year (higher values are permitted if the average over 5 years is not above 1 mSv a year)	15 mSv a year	50 mSv a year	-

MCNPX

Monte Carlo N-Particle eXtended (MCNPX) is a general-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo radiation transport code designed to track many particle types over broad ranges of energies. It is capable of simulating particle interactions of 34 different types of particles (nucleons and ions) and 2000+ heavy ions at nearly all energies [13].

The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and fourth-degree elliptical tori.

For photons, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung. A continuous-slowing-down model is used for electron transport that includes positrons, k x-rays, and bremsstrahlung but does not include external or self-induced fields.

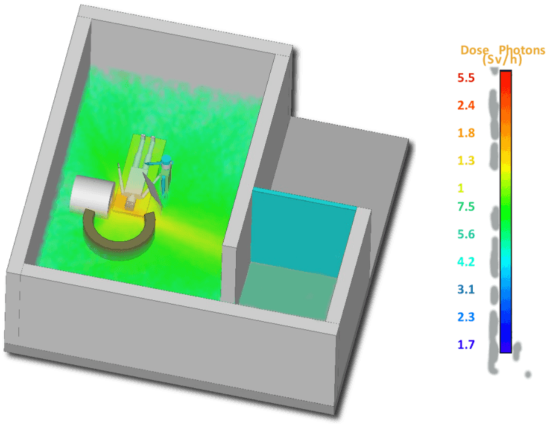


Figure 6. Illustrative image. Dose rate distribution in X-ray diagnostic room calculated by MCNP. https://www.physicsforums.com/attachments/carto-3d-medical-legende-modif-png.228998/

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.

Figure 6 shows a simple example of the MCNP modeling use in the field of medicine and radiological protection, applied to the determination of the dose rate distribution in a hospital room where diagnostic images are made in humans with the use of an X-ray machine.

Results

The SPECT technique requires the introduction, through an injection, of a certain biological molecule that has an affinity for the organ or part of the body under study. This molecule is linked to a radioisotope with a marker function, and whose radiations will be detected by the detectors of the SPECT system.

The first task consists of simulating, using the MCNPX, the emission and transport of the gamma radiation emitted by this marker, and determining the dose rate around the system.

For this, a group of point detectors were placed in the MCNPX input file at different distances from the source, and with them the fluence of particles at those points was measured. The results obtained in units of cm^{-2} are converted to units of dose, pSv, and then to µSv/h.

These dose rate values are compared to the safe limits established for occupationally-exposed workers to determine the safe distance from the source.

The figure 7 shows the dependencies obtained for different radiosotopes among the most used in SPECT tomography in an energy range from 73 to 511 keV. A visual magnification of the scale in the region of greatest interest is presented in Figure 8. In the figures itself, a line representing the value of the limit of dose considered safe was drawn.

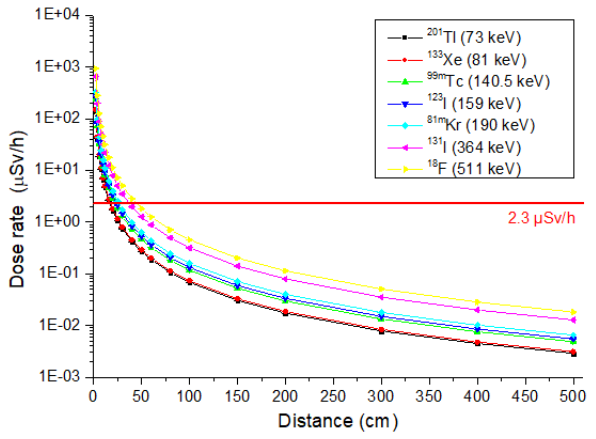


Figure 7. Dose rate vs. distance behavior calculated for seven common radioisotopes.

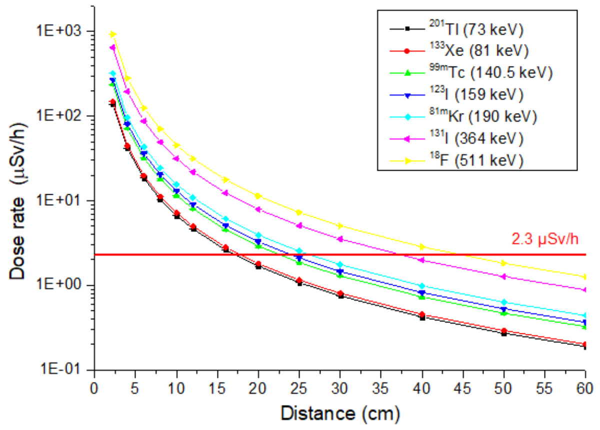


Figure 8. Zoom of the region near the center of coordinates in the dependence of the dose rate with the distance.

For the same activity of the sources, with the increase in the energy of the photons increases the distance that is considered safe from the point of view of radiological protection. In all cases the values are less than 45 cm. The exact values of this determination are presented in Table 2.

Table 2. Safe limit distance for each radioisotope.

Radioisotope	γ energy (keV)	Safe limit distance (cm)
^{201}Tl	73	17.6
^{133}Xe	81	17.8
^{99m}Tc	140.5	22.5
^{123}I	159	23.8
^{81m}Kr	190	26.1
^{131}I	364	37.2
^{18}F	511	44.4

Note that in this simulation no wall or other form of radiation protection is used. The point source is in the center of the mouse and reaches the detector through only the body of the animal and the air between it and the dose measurement point.

Now we are going to introduce near the mouse various obstacles (walls) that usually exist in all the SPECT scanner. We refer, for example, to the polypropylene bed that keeps the target immobile and moves it within the equipment, the duralumin gantry that holds and moves the detectors and the X-ray source, and a typical lead shield. Figure 9 presents a diagram of how this new geometric configuration results.

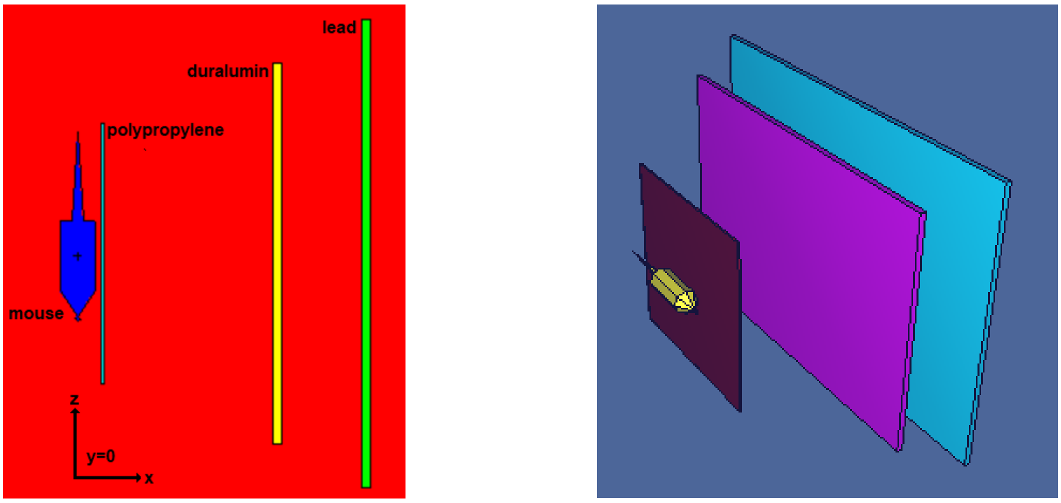


Figure 9. Schematics of the simulated geometric configuration with the introduction of three different typical walls.

The results of the simulation of the dependence of dose rate with the distance for the source of ^{99m}Tc, carried out without and with the introduction of the mentioned walls, are shown in figures 10 and 11. In these figures the inserted walls have been identified with bars of different colors, each one placed in the corresponding position in the simulated geometry and with the considered thickness.

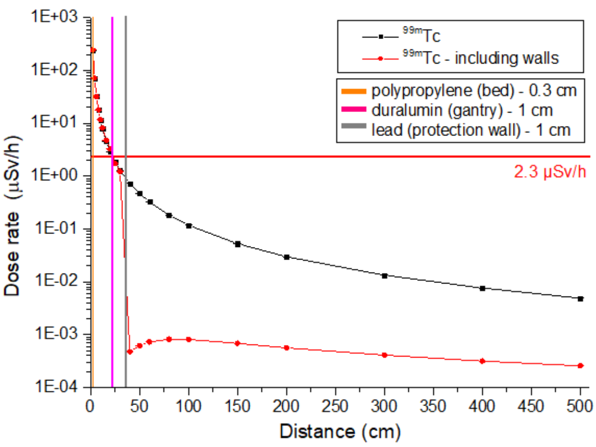


Figure 10. Dose rate vs. distance behavior calculated for ^{99m}Tc source in two different geometric conditions.

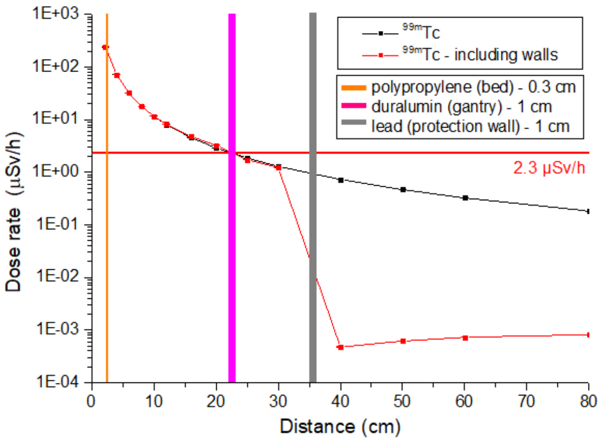


Figure 11. Zoom of the region near the center of coordinates in the dependence of the dose rate with the distance calculated for ^{99m}Tc source in two different geometric conditions.

These two figures show that the effect of the polypropylene bed and the duralumin gantry is almost imperceptible. However, the addition of the Pb shielding wall constitutes a strong barrier to the passage of radiation from ^{99m}Tc. In the graph of figure 11 it can be determined that 1 cm of lead causes that from a distance of 50 cm, the dose rate falls, depending on the position of the F5 detector, between **~ 95%** and **~ 99%.**

According to these results, the presence of lead shielding significantly increases the radiological safety around the system, however before the wall, that is, closer to the source, the results hardly change and the safety distance remains ~ 22 cm.

Now we are going to analyze the system when the configuration is CT, in that case the source used is X-rays, which is nothing more than a Roentgen tube placed on one of the axes perpendicular to the target. We are going to choose the X axis, and place the source directed to the mouse and the detectors that we are using.

The simulation is performed first without any wall obstructing the passage of the X-rays, only the presence of the mouse and the air. Then it will also be simulated including the same three classic walls that we placed in the previous study (see figure 9).

Figures 12 and 13 show the obtained results, the first on the entire scale, and the second on a scale restricted to the region near the center of coordinates. Columns colored and identified in figure 13, indicate the positions of the different walls in the arrangement.

As can be seen in figure 12, and with more details in figure 13, now the distance considered safe for occupationally exposed personnel has increased dramatically compared to the values obtained for isotopic sources. At very similar energies, the much higher flux of photons concentrated in a small cone directed towards the target and the detectors promote this effect. In the case of the simplest geometry, without any wall, this distance is **9800 cm**.

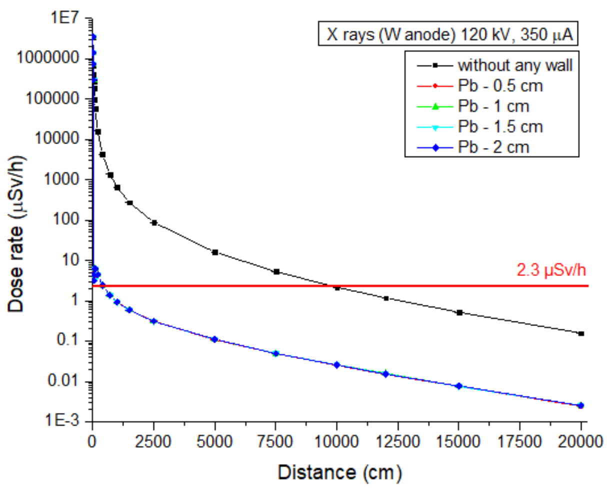


Figure 12. Dose rate vs. distance behaviors calculated for X-ray source and some different geometric conditions.

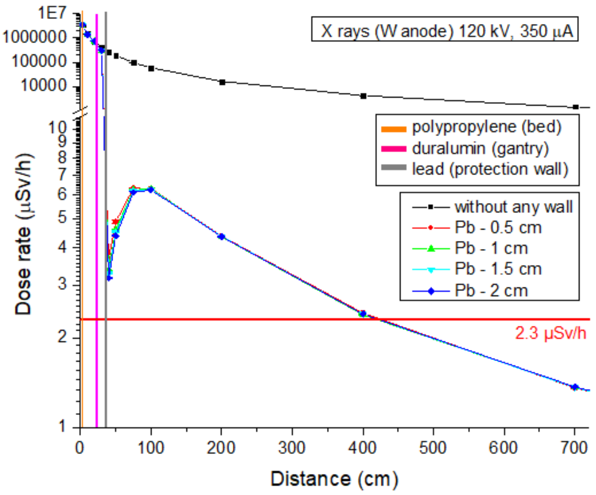


Figure 13. Zoom of the region near the center of coordinates in the dependences of the dose rate with the distance calculated for X-ray source and some different geometric conditions.

When introducing the proposed walls into the arrangement, it is observed that the thickness of the lead wall in this interval (0.5 - 2 cm) practically does not influence the result, that is, that for these thicknesses of Pb the distance considered safe will be the same, **420 cm**. This means that with this shielding wall it is possible to reduce this distance by ~ **96%**.

Conclusions

Considering that the radiation protection and safety is an extremely important issue within Nuclear medicine, both in its diagnostic and therapeutic methods, this work has been aimed at applying Monte Carlo simulation with the support of the MCNPX software to determine the dose rate distribution in some SPECT / CT scanner type geometric arrangements. These results are used to determine the distances considered safe for occupationally exposed personnel operating in equipment. The simulations were performed independently for the SPECT and CT setups. For SPECT, the simulation experiment was carried out for different radiosotopes in an energy range from 73 to 511 keV, verifying that with increasing photon energy the distance considered safe grows, but it was always less than 45 cm. All values are presented in the text. When some different walls are introduced in the studied geometry it was found that although polypropylene bed and the duralumin gantry have an almost imperceptible effect, the addition of the Pb shielding wall constitutes a strong barrier to the passage of radiation from ^{99m}Tc, decreasing the values of the dose rate between ~ 95% and ~ 99%. For the CT configuration, the use of the X-ray tube leads to a dramatic increase in the distance considered safe for occupationally exposed personnel. In the case of the simplest geometry, without any wall, this distance is 9800 cm, but introducing the proposed walls it is obtained that the distance considered safe falls to 420 cm regardless of the thickness of the wall of P in the interval studied; this represents a decrease in the distance of interest of ~ 96%.

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