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Structural Shielding Design of CT Facility using Monte Carlo Simulation

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ABSTRACT

Radiation application in medicine offers extraordinary benefits. But radiation is like a double-edged sword, it has both benefits and associated risks on the community in contact. To justify the safety of workers and members of the public, regulated use of radiation is assessed by the radiation protection protocols. The aim of this study is to design a Computed Tomography (CT) facility with a simplified model of CT scanner, whose shielding follows the guidelines of National Council on Radiation Protection and Measurements (NCRP) Report No. 147. To design the study model, Monte Carlo (MC) radiation transport code in MCNPX 2.6.0 was used for the simulation. Furthermore, MCNPX was used to measure the photon flux in a vicinity or the detector cell. To validate the functioning of the X-ray tube, the experimental results were compared with the X-ray Transition Energies Database of National Institute of Standards and Technology, U.S. Department of Commerce. The results obtained were within 0.60% of relative error. To confirm the functioning of shielding design, radiation protection quantity, air kerma was measured at several points outside, and inside of the CT room and they were under the radiation dose recommended by NCRP, which demonstrates that the shielding design was successful in blocking the radiation. The study can be used for an easy evaluation of any CT room within the framework of the model of the study.

1. Introduction

Ionizing radiation is made up of electromagnetic waves on the high-energy end of the electromagnetic spectrum (X-radiation and γ-radiation) and energetic subatomic particles (neutrons, β-particles, and α-particles) [1]. In the medical field, these ionizing radiations are used for diagnostic procedures, such as radiography, nuclear medicine, and computed tomography (CT), or for the treatment called as radiotherapy. Along with their benefits, they also pose serious health risks like cancer in humans, if not managed well. According to World Cancer Report (2020) published by World Health Organization (WHO), cancer is the second most common cause of death globally, accounting for an estimated 9.6 million deaths in 2018 [1]. Medical diagnosis alone contributes 20% of the average annual doses of ionizing radiation out of which, CT procedures lead much higher dose than conventional radiology [1]. Figure 1 shows the contribution of ionizing radiation doses from various sources.

X-ray computed tomography (CT) is a medical imaging modality that produces cross-sectional images representing the X-ray attenuation properties of the body [2]. Since the introduction of CT in 1970, it is ever-growing. It is estimated that more than 62 million CT scans per year are currently obtained in the United States alone, including at least 4 million for children [3].

To ensure the safety of medical team, patients, as well as the public from the ionizing radiation, CT facilities are built with special considerations so that people in the territory of the room don't get exposed to the radiation dose coming from the room. National Council on Radiation Protection and Measurements (NCRP) is such an organization that issues recommendations against radiation protection.

In this study, a virtual experiment close to the real CT environment was simulated in MCNPX 2.6.0 (Los Alamos National Security, LLC, USA) [4]. MCNPX is a MC transport code used as a modeling tool, capable of achieving a close adherence to reality, concerning the analysis of complex systems [5]. Considering particle interaction, this method follows every single particle emitted from a source to its death (absorption, escape, etc.). MC techniques are employed to accurately simulate the doses from radiation transport through matter [6]. In addition to simulation, MC allows geometrical modelling of macrobodies. In this study, the MC simulation was used to model the X-ray tube, standard CT Dose Index (CTDI) phantom, and the CT

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room. Also, it was used to measure photon flux in detector cells using F4 tally.

The designing of CT room was followed from the Datasheet of X-ray tomography installation in Instituto de Salud Publica del Estado de Guanajuato, Mexico, and NCRP Report 147 [7]. The design includes an X-ray tube emitting fan beam resembling to a CT equipment, a standard CT dosimetry phantom [8], and detectors inside and outside of the modelled CT room to study the shielding of CT facility from radiation emitted during the CT procedures.

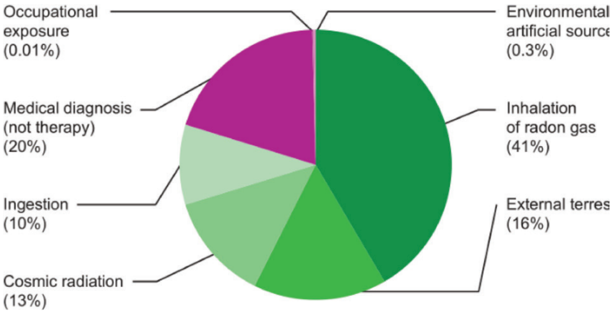

Figure 1: Average annual doses of ionizing radiation by source (*Source:* World cancer report 2020, WHO).

2. Materials and Methods

2.1. Modelling of X-ray Tube

In this work, an X-ray tube collimated to emit fan beam and a detector cell to contain the beam flux were modelled to resemble a CT device. The modelling was done using MC code in MCNPX. A defined electron source emitting a uniform beam of energy 140 keV was located at the distance of 0.3 cm from the Tungsten target of 5 mm thickness, 10 cm diameter, and 18.5° target angle. For the beam filtration the source and target arrangement were enclosed in Aluminum (Al) spherical shell of 2.5 mm thickness. To obtain a beam, the shell was put in cuboid made of lead, with a slit opening to collimate beam into fan shape. For further collimation, another lead collimator disk of 42 cm diameter and 5 mm thickness with an opening of 8cm X 4 cm was used. Figure 2a shows 2-D projection of X-ray tube with the collimator. The detector was simulated as a circular disk of 10 mm thickness and 38 cm diameter situated at the distance of 100 cm from the source. Figure 2b shows the 3-D view of the tube and detector arrangement simulated in MCNPX Visual Editor Version X_26 E, 2008, [9].

2.2. CT Dosimetry Phantom

A standard CT dosimetry phantom (FDA, 2003d; Shope et al., 1981) of head and body dimensions of 16 and 32 cm of diameters respectively, and 15 cm of length, were used in the study [8]. The phantoms were made of Polymethyl methacrylate (PMMA) or also known as Lucite. Figure 3 shows the head and body geometry of the phantom.

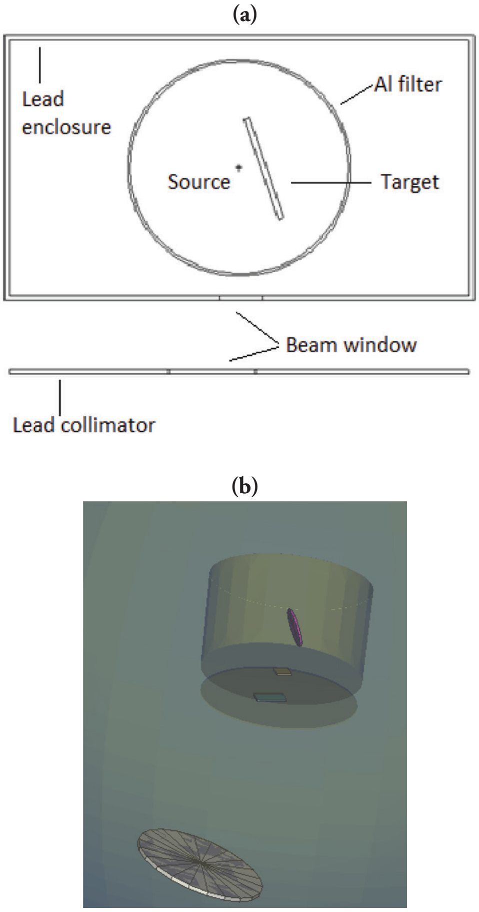

Figure 2: a) MC simulated X-ray tube geometry with its components in 2-D projection. **b)** 3-D visualization of X-ray tube and the detector in Visual Editor.

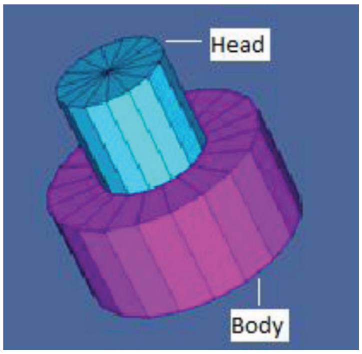

Figure 3: Standard dosimetry phantom visualization in Visual Editor.

2.3. Shielding Materials

The material and dimensions for designing the CT room were chosen in combination from Datasheet of X-ray tomography installation in Instituto de Salud Publica del Estado de Guanajuato, Mexico, and NCRP Report 147. Barite concrete, lead, red brick, plywood door, and lead glass materials were used as radiation protection materials.

2.4. CT Room Elements

The structure of the room contains a window, and a door for the control room, three doors for the dressing room, washroom, and the storeroom, respectively. Also, ceiling, and the floor. The floor and the ceiling were made of concrete while the walls were made of concrete layer and red brick with a lead sheet sandwiched between them. The control room window was made of lead glass. The doors were made of plywood with a lead sheet covering.

3. Results

3.1. X-ray Tube Evaluation

The X-ray tube and the detector arrangement resembling to a CT device could produce a fan beam. Figure 4a shows the confined X-ray fan beam simulated for 10^6 particles in Visual Editor. Furthermore, the MC code was run for 10^8 particles and the photons were collected at the detector. The fluence of the particles in the energy range of 0-140keV were plotted. Figure 4b shows characteristics X-ray spectrum of the tube.

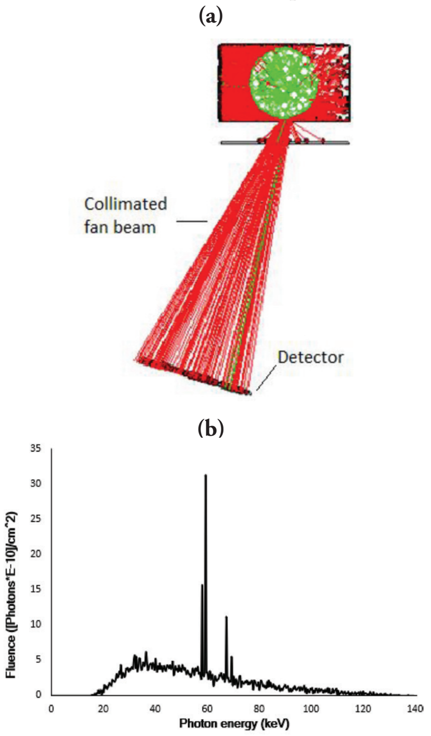

Figure 4: a) MC simulation of X-ray fan beam of 140 keV. Red and green tracks represent photons and electrons trajectories, respectively. **b)** Characteristics X-ray spectrum for 10^8 particle histories.

For the validation of X-ray tube model, the values of characteristics transitions of the X-ray tube operating at 140keV obtained by MC simulation were compared with the X-ray Transition Energies Database of National Institute of Standards and Technology (NIST), U.S. Department of Commerce [10], and the values were within 0.60 % relative error. Table 1 shows the transition values and the associated errors.

Table 1: Comparison of simulated X-ray transition values with the values of NIST database.

Transitions	NIST database	MCNPX simulation	%Relative error
K-beta2	69.10 keV	69.5 keV	0.58
K-beta1	67.24 keV	67.5 keV	0.38
K-alpha1	59.32 keV	59.5 keV	0.30
K-alpha2	57.98 keV	58.2 keV	0.38

3.2. Shielding Design Validation

The complete model of shielding design of CT facility that includes X-ray tube, the phantom, and the detector were simulated in the Visual Editor. Figure 5 shows the simulated model with all its components. To validate if the shielding design functions to shield the radiation generated by the X-ray tube, and the scattered radiation from the phantom surface, radiation values must be under the levels recommended by NCRP. In terms of air kerma, it recommends 0.1 mGy per week air kerma value inside the CT room while 0.02 mGy per week air kerma value outside the CT room. To test that, various point detectors of 2 cm exclusion radius were put outside and inside of the CT room at 5 cm distance from each barrier such as walls, doors, and window, using F5 tallies. The code was then run for 2×10^8 number of particles. For air kerma, the tally outputs were recorded in the units of pico-grey per history (pGy/history). Then, this unit was converted into milli-grey (mGy). To validate if the shielding fulfils the goal, the values were tallied in accordance with NCRP recommended values, and all the measured air kerma values were way below the recommendation of NCRP. Hence, the design was successful to shield the radiation.

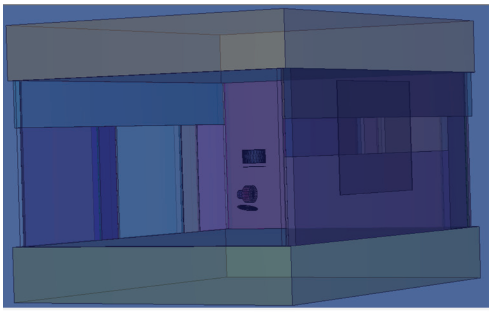

Figure 5: Complete shielding design of CT facility consisting X-ray tube, a standard phantom, a detector surface under phantom, and the room with radiation shielding capacity.

4. Discussion

Although the shielding design may not be optimum in terms of its construction, but it does validate the idea of shielding and how MCNPX can be used by radiation experts to test their shielding plan before bringing it into real practice.

Conclusions

In the study, results point out that the model can be used for visualization of a CT facility that includes the most relevant components, using MC code. Furthermore, the functioning of the X-ray tube could be validated with the X-ray transitions data of NIST. The justification of safety from radiation comes with the fact that no radiation was detected outside the room supporting the recommendations of NCRP report. This model provides an insight of the shielding idea that can be used as a tool to verify any shielding plan of CT installment before onsite construction. This idea helps experts to design, visualize, and tailor their shielding plan.

Conflict of interest

The authors declare that they have no conflict of interest.

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