A Monte Carlo shielding model for PET/CT clinics

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Abstract

Modern PET/CT clinics consist of a scanner room housing the double gantry PET/CT unit and a control area, two or more quiet rooms where patients rest prior to scanning, and a hot lab where doses are prepared. Of these areas, the scanner room, quiet rooms, and frequently the hot lab require structural shielding to protect staff and personnel in surrounding areas. The 511 keV photons from the PET positron emitting isotopes are the source term for the quiet rooms and the hot lab, while both the 511 keV photons and the polyenergtic spectrum of x-rays from the CT unit must be considered for the scanner room. We have developed a three dimensional model of the PET quiet rooms and the PET/CT scanner room for the Monte Carlo code MCNP Ver 5 , and for the Mercurad shielding code. The quiet room model consists of a MIRD phantom in a reclining position with 555 MBq (15 mCi) of ^{18}F distributed in the brain and bladder. All room structures to include the layered floor and ceiling shields are modeled. For the scanner room, the double gantry of the PET/CT unit is modeled as two rings with dimensions and attenuation based on a current PET/CT unit. The MIRD phantom is positioned prone in the scanner and source term of 277 MBq (7.5 mCi) is distributed in the patient. Thirty percent of the dose is located in the patient's head, with the remainder distributed throughout the body. Room structures, to include the layered floor and ceiling shields are developed. The model is a useful tool for accurately determining required shielding in surrounding areas, particularly for the floors and ceilings, which are complex layered shields that are not easily handled by point kernel shielding methods.

Key Words: Shielding, Monte Carlo, point kernel, positron emission tomography

Introduction

Positron Emission Tomography (PET) is enjoying explosive growth due to its ability to accurately stage many types of cancer and follow the progress of treatments. The facilities present unique challenges in shielding design due to the nature of the study, and the desire to place the facilities near other imaging and treatment clinics.

A typical PET patient will receive 555 MBq (15 mCi) of ^{18}F labeled 2-Fluoro-2-Deoxy-D-Glucose (FDG) and will rest in a darkened room (called a quiet room) for 45 minutes to allow the drug to localize in the lesions of interest. A normal clinic will have one to three quiet rooms. While in the quiet room, the patient will normally recline in a comfortable lounge chair.

The distribution of the FDG in the patient will vary from patient to patient, but much of the isotope will be located in the brain and the bladder. After resting for approximately 45 minutes, the patient is asked to empty his or her bladder, and is placed on the scanner bed. Images are collected for 30 to 45 minutes on the PET or combined PET/CT unit. The patient is then released after the scanning is complete.

PET clinics also have a hot lab where the ^{18}F doses are stored, checked in a dose calibrator (well ion chamber) to determine the administered activity, and placed in a syringe shield prior to administration to the patient. Wastes are also temporarily stored in the hot lab. For most clinics, the labeled FDG is delivered in unit dose form from a centralized radiopharmacy just prior to the patients' arrival. One to three shielded transport boxes with doses in them are present in the hot lab during the scanning day. For a properly designed hot lab, all handling and storage of the PET isotopes is performed behind a heavily shielded "L" block and cave of interlocking lead bricks to limit dose the technologist. Similarly, syringe shields designed for PET isotopes and leaded transport boxes are used to protect the technologist during the transport of the drug to the injection area and during the injection.

For clinics where occupied areas are adjacent to the PET clinic, shielding is required for the patient quiet room(s), the hot lab, and the scanning room.

Design Dose Limits, Use, And Occupancy

1.2 Design Dose Limits

The design limit for the restricted areas was chosen as the pregnant worker limit of 5 mSv over the term of the pregnancy for a declared pregnant worker. The design limit for unrestricted areas was the non-occupational dose limit of 1 mSv per year[5]. In many European countries the design dose limit is constrained to 1/4 of this value.

1.3 Room Use Factors

In this work we conservatively estimate that the quiet room is continuously occupied by a dosed patient when only one quiet room is provided in the design. When multiple rooms are provided, a use factor of 0.56 for each room was used based on observations made in operating clinics.

Clinics are designed to keep the PET or PET/CT unit running as much as possible, so a use factor of 1.0 was used for the scanning room. All modern PET?CT scanners provide significant attenuation of the photons emitted within them, but it is difficult to quantify the total attenuation provided as the patient is traveling through the scanner and the patient’s head, where approximately 30 percent of the FDG is located, is out of the scanner for most of the imaging time. In this work, we modeled the double gantry of the PET/CT unit and major supporting structures to provide accurate estimates of attenuation.

The use factor for the hot lab was also considered to be 1.0 due to the presence of the transport boxes with doses in them for most of the scanning day. For unit dose clinics, the actual handling of the doses behind the shielded “L” block contributes little to the doses in adjacent areas.

1.4 Occupancy Factors

Occupancy factors for adjacent areas may be determined from realistic estimates or from prescribed limits, depending on the regulatory environment. For this work, the hot lab and the PET/CT control were considered to be fully occupied by occupationally exposed personnel and adjacent office suites where the licensee had no control of the facility were considered to be fully occupied by non-occupationally exposed personnel. Other occupancy factors were derived from values presented in NCRP 147 [5].

The Models

Wall shielding is constructed of commercial sheet lead and can easily be calculated using point kernel techniques [2,3,] with appropriate buildup factors. When occupied areas exist above or below the PET clinic, however, the shielding is constructed of the existing concrete floor deck and commercial sheet lead applied to the top of the floor, or, more commonly, suspended from the floor joists. Concrete floor decks in medical office buildings typically range from 5 to 15 cm in thickness, while hospitals designed for heavy floor loading can exceed 20 cm in thickness. The concrete floor decks in existing structures may be constructed of normal density concrete (2.35 g/cm^3) or lightweight concrete, and the poured thickness may vary from the specified amount by 1 cm or more. The layered lead and concrete shield is difficult to estimate by point kernel techniques as the energy of the photons incident on each layer is difficult to determine, as is the pass off of scattered photons from layer to layer. Nonetheless, the accuracy of the floor and ceiling shielding estimate is important as much of the cost of the total clinic shielding is driven by the construction costs related to the suspended lead. Consequently, a Monte Carlo model for MCNP 4C [1] was developed for a generic PET clinic so that it could be easily modified for specific clinic designs. A second model was developed for Mercurad [8], a deterministic model designed specifically for layered shields. The models may be used to provide facility-specific shielding designs by simply modifying the dimensions of the rooms and concrete deck thickness to match those found in individual facility design plans.

1.5 Monte Carlo Model

The Monte Carlo model of a PET clinic was originally developed when point kernel calculations at one facility indicated that two courses of 0.635 cm (1/4 inch) Pb would be required to protect the office space above the quiet rooms. The additional lead would have required structural reinforcement of the ceiling and increased the cost of the clinic shielding substantially.

The quiet room model, shown in Fig. 1, consisted of a male MIRD [4] anthropomorphic model modified to a sitting posture [6] inside a room. The inside room dimensions, taken from design plans for the clinic, were 2.43 m (8 feet) along the human model axis, 2.13 m (7 feet) across, and 3.67 m (12 feet) high. The bottom of the human trunk was centered in the room approximately 0.67 m above the floor. A transformation applied to the room resulted in a reclining position with the vertical axis of the human model at 30° relative to the room vertical. (The human model was not transformed to facilitate source positioning.)

The ceiling above the clinic consisted of standard density concrete (grey in Fig. 2) on a 0.076 cm (22 gauge) thick corrugated steel deck (green) below which was a 0.635 cm (1/4 inch) thick lead layer (black). The steel was modeled as a flat layer without corrugations. The concrete varied in thickness from 8.89 cm to 15.24 cm. The locations of the thicker sections of the concrete could not be reliably located with regard to the critical rooms in the PET clinic so only the thin sections of the floor were modeled. The floor was a 8.89 cm (3.5 inches) thick layer of concrete. The walls consisted of a 0.635 cm (1/4 inch) lead layer sandwiched between 1.59 cm (5/8 inch) layers of gypsum wallboard (blue in Fig. 2).

The source term for this model consisted of 555MBq of ^{18}F split evenly between the brain and the bladder in the MIRD phantom. Self-attenuation of photons in the patient is correctly modeled in this manner. The Moritz code [7] was used to plot the positions of a few hundred source points to verify that the source was confined to the brain and bladder.

The scanner room was also modeled from plan dimensions and had the same floor, ceiling, and wall structure as the quiet rooms discussed above. The PET/CT scanner was modeled based on figures provided by GE for their current PET and Multi-Slice CT unit, but may be extrapolated to all modern PET/CT units with multi-slice CTs. The model, shown in Figure 3, consists of iron PET and CT rings around an adult MIRD phantom with a thickness to match the attenuation of the actual rings (provided by Jay Williams, Ph.D., GE Healthcare).

Of the 15 mCi initial dose of ^{18}F, 7.5 mCi is assumed to remain after the patient has rested in the quiet room for 45 minutes and then urinated before being scanned. Thirty percent of this activity is assumed to be in the brain, which is always outside of the scanner, and the remainder is distributed throughout the patient's body.

1.6 Tallies [Ken describe the mesh tallies used above and below the quiet rooms and the scanner room]

Results: [Ken describe mesh tally results and add figures]

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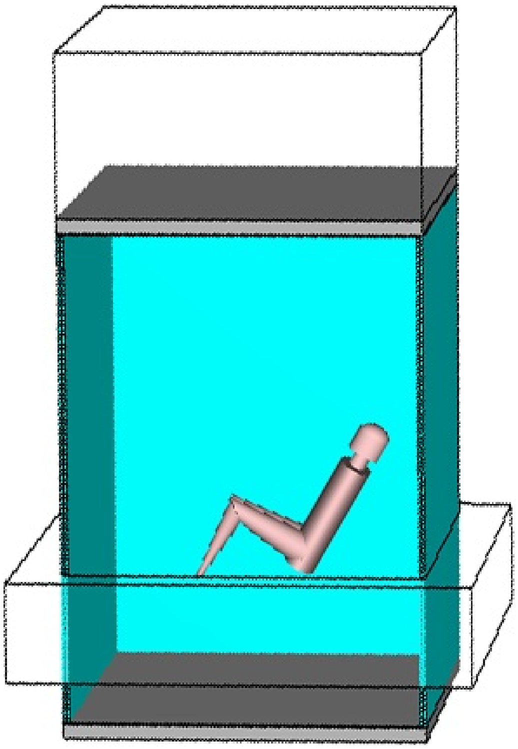

Fig. 1 Monte Carlo model of a PET quiet room with external air spaces outlined.

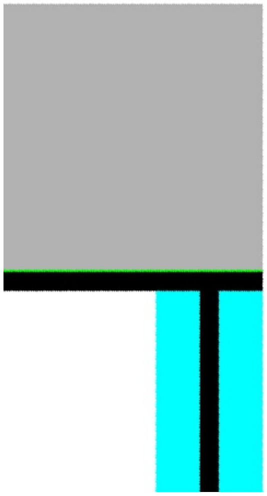

Fig. 2 Detail of cross section of wall and ceiling.

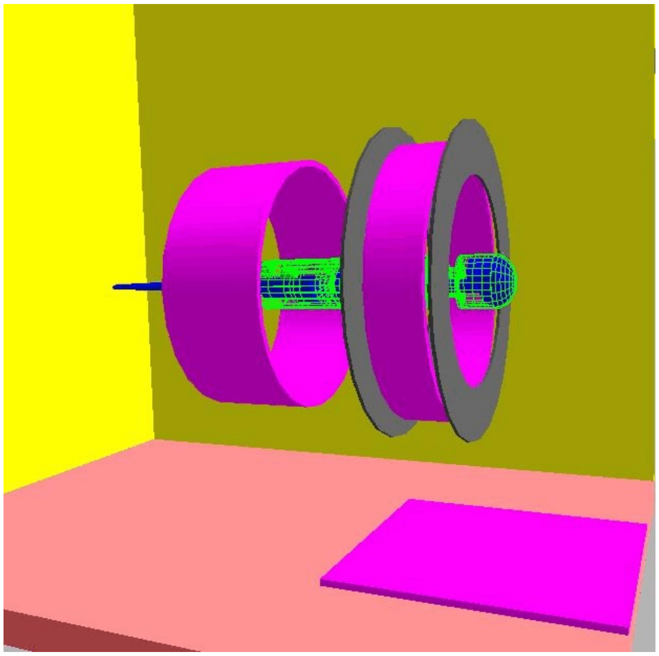

Figure 3. Monte Carlo Model of the PET/CT Unit