Monte Carlo 2005 Topical Meeting
Chattanooga, Tennessee, April 17-21, 2005, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2005)

LAYERED SHIELDING DESIGN FOR PET CLINICS

Robert L. Metzger and Kenneth A. Van Riper
Radiation Safety Engineering, Inc
3245 North Washington Street, Chandler, AZ 85225
rlmetzger@radsafe.com; kvr@rt66.com

ABSTRACT

The number of Positron Emission Tomography (PET) centers has been growing rapidly. Many of the new facilities have been retrofitted into existing imaging centers and hospitals. Space in the facilities is often cramped, resulting in the hot lab, patient quiet rooms, and the scanners frequently being placed in close proximity to uncontrolled areas where non-occupational dose limits apply. Of particular concern are ceilings when occupied areas are above the PET clinics. Ceiling shielding is generally constructed of layers of suspended lead, steel, and the existing concrete floor of the deck above. The attenuation provided the layered shield is difficult to calculate by point kernel techniques, yet the cost of overshielding can be high when lead must be suspended from the floor above. In this work we evaluate ceiling shielding for a proposed PET center using different methods. A Monte Carlo calculation using MCNP modeled the patient with a sitting MIRD anthropomorphic model in which 15 mCi of ^{18}FDG is distributed equally among the brain and bladder. A point kernel calculation was made using Mercurad, a code designed to manage attenuation in layered shields. The results from the two models are compared to each other and to measurements conducted on the finished PET clinic.

Key Words: Shielding, Monte Carlo, point kernel

1 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.

2 DESIGN DOSE LIMITS, USE, AND OCCUPANCY FACTORS

2.1 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.

2.2 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 PET 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 much of the FDG is located, is out of the scanner for most of the imaging time. No credit was taken for scanner attenuation in this work.

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.

2.3 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. Corridors were assigned an occupancy of 1/4, unoccupied landscaping 1/16, and adjacent office suites where the licensee had no control of the facility 1.0.

3 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, a deterministic model designed specifically for layered shields. The models were used to estimate the shielding for the quiet rooms for a PET clinic under design, and the results were compared to actual measurements taken once the facility became operational.

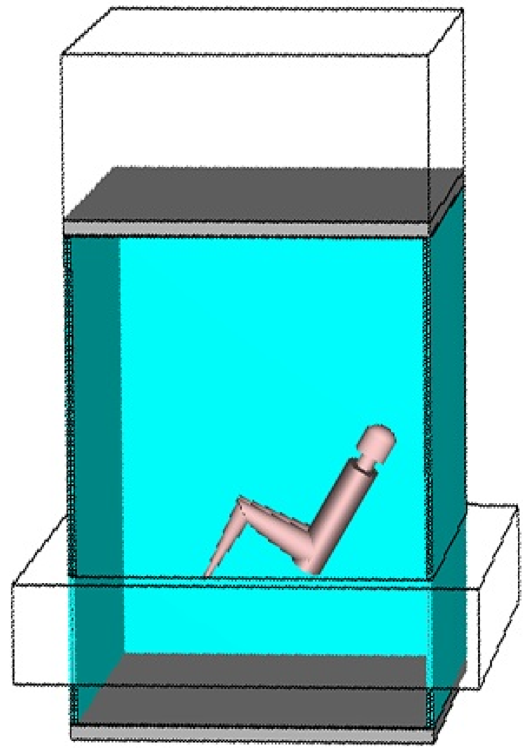

Figure 1. Monte Carlo model with external air spaces outlined.

3.1 Monte Carlo Model

A Monte Carlo model of the quiet rooms at a new PET clinic under design was developed when point kernel calculations 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 model, shown in Fig. 1, consisted of a male MIRD [4] anthropomorphic model modified to a sitting posture [5] 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 30º 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

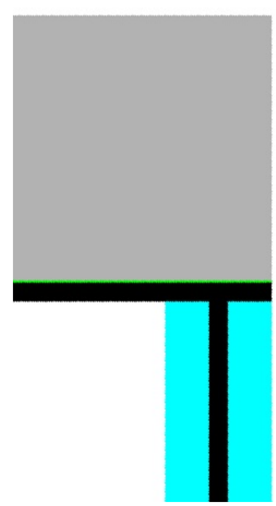

Figure 2. Detail of cross section of wall and ceiling.

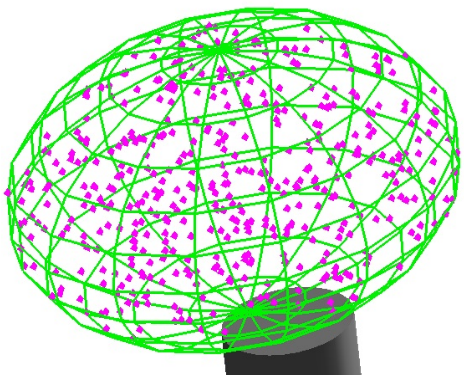

Figure 3. Brain source points.

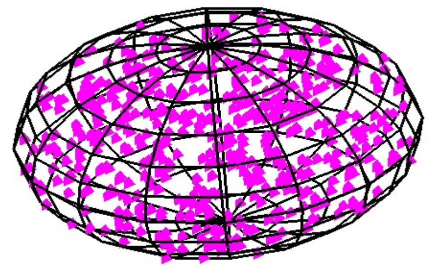

Figure 4. Bladder source points.

(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 [6] was used to plot the positions of a few hundred source points to verify that the source was confined to the brain and bladder (Figs. 3 and 4).

Tallies were taken in a 1.1 m thick air space above the ceiling. The thickness was based on the average height of an office worker's chair. Additional air spaces exterior to the walls (outlined in Fig. 1) were included to accommodate future studies where the exposure rate in neighboring rooms might be of interest. Several layers of importance splitting through the ceiling were used to enhance the statistics in the space above.

3.2 Mercurad Model

Mercurad [7] is a recently developed shielding code designed specifically for designing layered shields using iterative methods for calculating buildup factors. The graphical user interface allows 3D geometries of sources, shields, and detectors to be developed quickly. Complex structures, such as the MIRD phantom used in the MCNP model, are not available for this code.

The model for this code consisted of a water filled sphere 10 cm in diameter filled with 555 MBq of ^{18}F and positioned 70 cm over the floor to match the patient position in the recliner. No patient self-attenuation is considered in this model. The 0.635 cm (1/4") Pb sheet, and 8.89 cm concrete deck of the second floor were modeled as noted above. A detector set to record the exposure rate was positioned 60 cm above the floor deck. The irregular corrugations in the concrete were also not considered in this model.

4 RESULTS AND MEASUREMENTS

Once the models were complete, the MCNP model was run for 5 x 10^7 photons. All ten of the MCNP statistical tests for the tally above the shielded room passed, and the estimated weekly exposure for the office above the quiet room is shown in table 1 below. The Mercurad model was also run and produced the results shown in Table 1 below. Both models show the estimated exposure rate near the 2 mR/wk limit for non-occupationally exposed personnel and full occupancy. The estimates were considered conservative, however, as floor coverings, the floor trusses and supports, and mechanical equipment installed above the false ceilings in the quiet rooms provide some attenuation. The Mercurad results were predictably higher than MCNP as patient self-attenuation was not considered in this model. If the Mercurad result is factored for patient self-attenuation (dose at one meter ~65% of the unattenuated point source [8]), the predicted exposure rate would be 1.5 mR/wk from this model. Both estimates were well below the hand point kernel results which calculated the attenuation from each layer independently and summed them [8].

Once the facility was constructed and operational, measurements of the exposure rates in adjacent areas were performed with a Radcal Model 10X5-1800 ion chamber which was able to measure the low predicted transmission rates with a short integration time. The measured results with a patient who had received 555 MBq of ^{18}F in each of the quiet rooms of the PET clinic are shown in the table below. The measured results were lower than predicted values due to mechanical equipment that was installed in the interstitial space between the false ceiling above the rooms and the corrugated concrete which increased the attenuation above quiet room 1.

Table I. Predicted and Measured Radiation Exposures in Offices Above the PET Quiet Rooms (mR/wk)

Location	Predicted MCNP	Predicted Mercurad	Observed
Office Above Quiet Rm 1	1.96	2.28	0.29
Office Above Quiet Rm 2	1.96	2.28	0.86

5 CONCLUSIONS

Both the MCNP and Mercurad models provided superior estimates of radiation levels penetrating the layered concrete and lead shields that comprised the ceiling above the quiet rooms of the clinic under design as compared to point kernel calculations treating each section of the layered shield independently. Conversations with the architect for the site and the construction manager indicated that the cost savings in reducing the ceiling lead from 1.27 cm called for by the point kernel calculations to 0.635 cm of lead was $8,000 to $12,000 including the cost of the materials, structural reinforcement, and the labor to install the additional shielding. The cost of running the transport or Mercurad models is a small fraction of the savings realized.

6 REFERENCES

1. J.F. Briesmeister, ed.. *MCNP A general monte carlo N-Particle transport code version 4C*. Los Alamos National Laboratory Manual LA-13709-M, (April 2000).
2. Chilton A, Faw R, Shultis J, *Principles of Radiation Shielding,* Prentice-Hall, Englewood Cliffs, USA (1984).
3. D.K. Truby, et. al.,Gamma-ray attenuation coefficients and buildup factors for engineering materials," *American Nuclear Society,* **ANSI/ANS-6.4.3-1991,** (1992).
4. M. Cristy and K. F. Eckerman, *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. I. Methods*, Oak Ridge National Laboratory Report ORNL/TM-8381/VI (1987).
5. R. H. Olsher and K. A. Van Riper, Application of a Sitting MIRD Phantom for Effective Dose Calculations, *Proceedings of the ICRS-10/RPS 2004 Conference*, 9-14 May 2004, Funchal, Portugal (in press).
6. K. A. Van Riper, Interactive 3D display of mcnp geometry models, *Proceedings of the ANS International Meeting on Mathematical Methods for Nuclear Applications*, Salt Lake, UT, Sept. 10-13 (2001).
7. MECURAD Dose Rate Calculation Software. Canberra Industries, 800 Research Parkway, Meriden, CT , USA (2003).
8. M.T. Madsen, J.A. Anderson, et.al.,Draft AAPM Guide on PET and PET/CT Shielding Requirements, AAPM (2004).