Radiation Safety Considerations for PET Centers

Terry F. Brown and Nicholas J. Yasillo

Franklin Mclean Memorial Research Institute, Department of Radiology, The University of Chicago, Chicago, Illinois

This article explains why technologists handling positron-emitting radionuclides may have higher measured radiation exposures than technologists working with single-photon emitting radionuclides. We will summarize measurements we have made, as well as those reported by other authors. In addition, we will describe the procedures implemented to minimize exposure.

Key Words: facility design; PET; radiation monitoring; radiation safety

J Nucl Med Technol 1997; 25:98–102

Technologists handling positron-emitting radionuclides often have whole-body and extremity exposures that are twice as high as exposures for technologists working with single-photon emitting radionuclides (*1*). A number of factors contribute to these higher exposures, including: the ionizing potential of the positron, the energy of the resultant annihilation gamma photons, the quantity of radionuclide routinely administered and additional exposure generated during procedures associated with data gathering necessary in quantitative metabolic function studies. In this article, we will explain how each of these factors can result in higher radiation exposures and describe the measures that we and others have implemented to keep these exposures as low as reasonably achievable.

IONIZING POTENTIAL OF A POSITRON

When a positron interacts with an electron, the resultant annihilation process converts the mass of the two oppositely-charged particles into two 511-keV gamma photons (Fig. 1). While the energy of these gamma photons is the same for all positron-emitting radionuclides, each positron emitter has a characteristic spectrum of positron energies based on the sharing of the initial energy between the positron and the neutrino. The distance the positron travels, prior to its annihilation, is directly proportional to its initial energy and inversely proportional to the density of the material it is being absorbed in. Listed in Table 1 are the characteristics of the radionuclides commonly used for PET (*2*). The maximum and mean positron energies are listed, as well as the range or maximum distance these particles can travel in air and water.

Generally, plastic is a better attenuator of positrons than water. A disposable plastic syringe has a wall thickness of approximately 1 mm. Some ^{18}F positrons and most of the positrons emitted by ^{15}O and ^{82}Rb are able to penetrate the syringe wall and produce ionizing events outside of the syringe. In air, the ^{15}O positrons at E_{max} can travel over 6 m and ^{82}Rb positrons at E_{max} can travel almost 12 m before being totally absorbed.

Figure 2 shows that anyone in the scanning room of the University of Chicago PET Center would be within the range of ^{15}O positrons and persons working in the inner circle (1.5-m radius) are within the range of the most energetic (E_{max}) ^{18}F positrons. Because the thickness of conventional building materials is sufficient to absorb the energy of a positron, there will be no positron exposure to the staff working outside the scanner room. By keeping the doors closed, all of the positrons will be absorbed within the scanning room.

ANNIHILATION PHOTONS

A second potential hazard of positron-emitting radiopharmaceuticals is the additional penetrating power of 511-keV gamma photons, especially when compared to the 140-keV photons of ^{99m}Tc (Table 2). Because of the greater penetrating power of 511-keV gamma photons, it is necessary to be aware of not only the potential exposure to staff working in the scanning room, but also the potential exposure to people in adjacent rooms including unmonitored clerical or other support staff and visitors.

Tables 3 and 4 summarize results we have previously reported (*3*) of radiation intensities measured with a G-M tube (Model 3 Survey Meter with Model 44 G-M tube, Ludlum Measurements, Sweetwater, TX) at different locations in our PET center during PET studies and from a 858.4-MBq (23.2-mCi) source of ^{99m}Tc and a 384.8-MBq (10.4-mCi) source of ^{18}F, centered on the scanning bed. Table 3 gives the radiation intensities measured in the scanning room and in two adjacent rooms. Table 4 shows the results of measurements made in areas occupied by clerical, other support staff and visitors.

For correspondence or reprints contact: Terry F. Brown, BS, CNMT, MIICRO, Inc., 1021 West Adams St., Suite 107, Chicago, IL 60607.

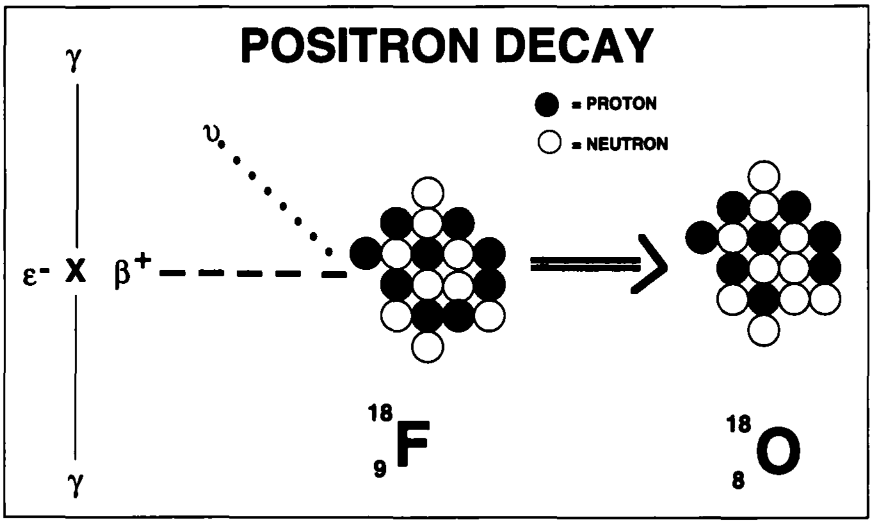

FIGURE 1. Positron decay occurs when an atom has an excess of protons relative to the number of neutrons in its nucleus. A positron is ejected from the nucleus of an atom with an initial energy equal to the difference in nuclear binding energies of these two atoms, less any energy used to eject a second particle from the nucleus which is called a neutrino.

The ratio of exposures at Location F should be of interest to centers considering placing a PET scanner in an existing nuclear medicine department or using an existing gamma camera to image ^{18}F. This measurement was made through a wall consisting of two sheets of 1-inch-thick drywall. Since the amount of ^{99m}Tc administered for many nuclear medicine procedures is twice the amount of ^{18}F routinely administered, the background in adjacent rooms might only increase by a factor of two. A significantly higher increase in peak room background rates would result if ^{82}Rb were being used since 1.85-GBq (50-mCi) doses are routinely administered (*4*). Another consideration in this setting, but one we did not evaluate, is how effective existing gamma camera shielding would be for these higher energy photons originating in an adjacent room.

The radiation levels we have measured are consistent with those reported by Kearfott et al. (*5*). Using a calibrated ionization chamber (Bicron RSO-5, Bicron Corporation, Newbury, OH), they measured an average radiation exposure of 0.11 mGy/hr/MBq (0.15 mR/hr/mCi) at a distance of 1.5 m from a source of ^{18}F. These authors also report measured exposure rates at 0.25, 0.5, 1.0 and 1.5 m from sources of each of the radionuclides listed in Table 1. Using this information, as well as projected annual workloads, one can evaluate the potential radiation exposures in areas where positron-emitting radionuclides will be used.

QUANTITY OF RADIONUCLIDE ADMINISTERED

The short physical half-lives of positron-emitting radionuclides allow significantly higher quantities of radiopharmaceutical to be administered, resulting in staff exposures that can exceed regulatory limits. For a study of cognitive function, a single subject may receive as many as six successive 2.22-GBq (60-mCi) doses of ^{15}O water (*6*). Shown in Table 5 are the pocket dosimeter (Model 862, Dosimeter Corporation, Cincinnati, OH) readings that we observed during such a study. In addition to the whole-body exposures shown in Table 5, the hand exposure for the person preparing the radiopharmaceutical for these studies can be up to 4 mSv (400 mrem) per study with the person administering the radiopharmaceutical receiving a hand exposure of up to 2.5 mSv (250 mrem).

QUANTITATIVE MEASURES OF METABOLIC FUNCTION

One advantage of PET is the capability of actually measuring metabolic processes (*7*). This requires an accurate measurement of the quantity of radiopharmaceutical available to the organ at the time of imaging. This information is typically obtained by drawing a series of blood samples during the study. McCormick and Miklos found that staff exposures during

TABLE 1
Characteristics of Common Positron-Emitting Radionuclides

	E_{B+}^{max} (MeV)	Range in water (mm)	Range in air (m)	$\bar{E}_{B+}$ (MeV)	Range in water (mm)	Range in air (m)
^{18}F	0.635	2.15	1.66	0.212	0.46	0.36
^{11}C	0.970	3.80	2.94	0.323	0.85	0.66
^{13}N	1.200	5.00	3.87	0.400	1.15	0.89
^{15}O	1.740	8.00	6.19	0.580	1.80	1.39
^{68}Ga	1.900	9.00	6.96	0.633	2.15	1.66
^{82}Rb	3.150	15.50	11.99	1.050	4.10	3.17

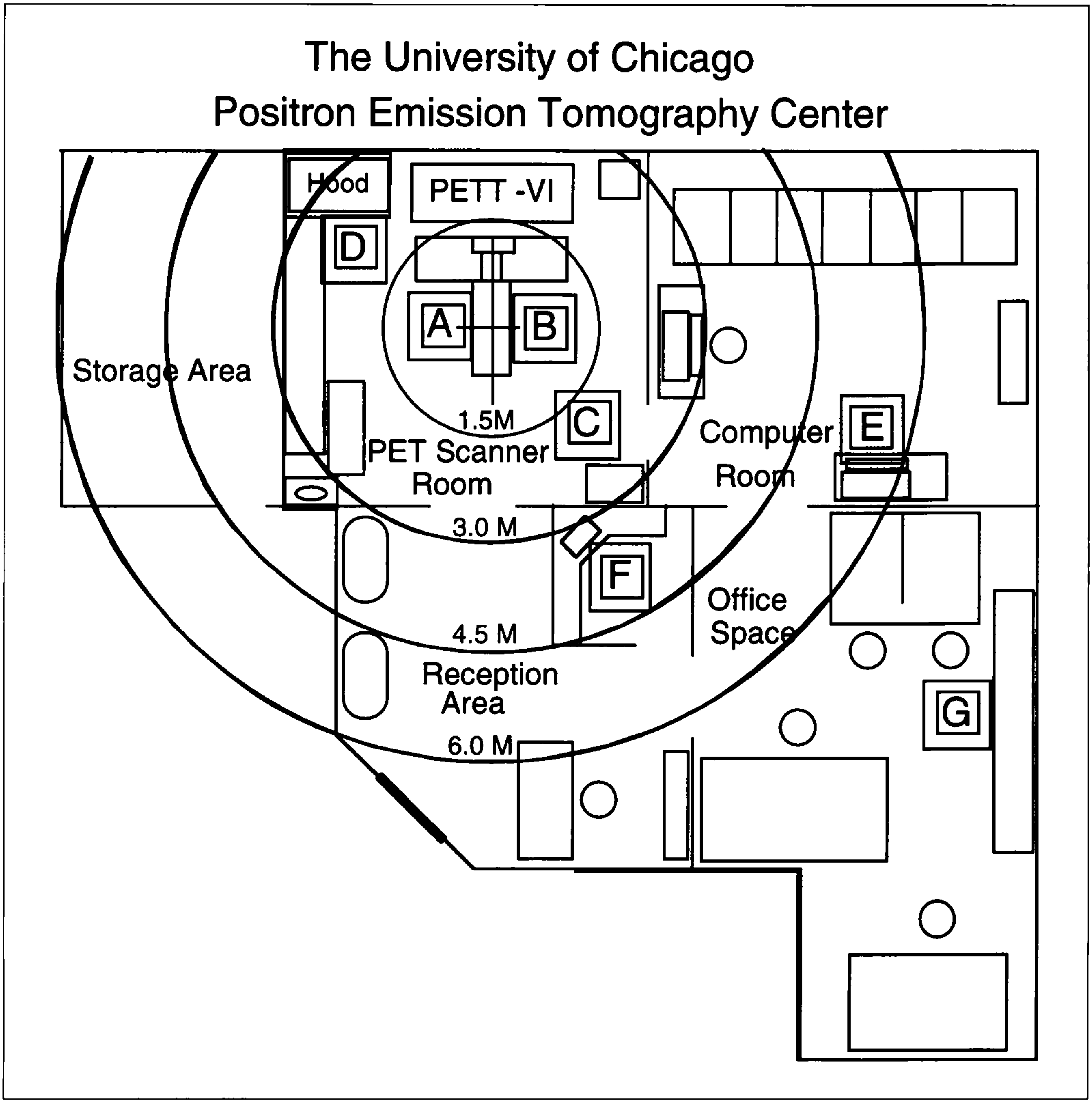

FIGURE 2. A scale drawing of the PET Center at the University of Chicago. The letters indicate the approximate location of the staff involved in a positron tomography study, with the distances from the center of the scanner shown by the circles.

TABLE 2
Comparison of Shielding Material Half-Value Layers*

keV	Lead (mm)	Tungsten (mm)
150	0.3	0.2
500	3.8	2.6

*Data from reference *2*.

TABLE 3
Radiation Exposure by Location mGy/hr/MBq (mR/hr/mCi)

Location	^{18}F	^{99m}Tc	Ratio
C	0.0875 (0.125)	0.0329 (0.047)	2.7
E	0.0147 (0.021)	0.0021 (0.003)	7.0
F	0.0098 (0.014)	0.0021 (0.003)	4.7

TABLE 4
Radiation Exposures in Adjacent Rooms During PET Studies μGy/hr (mR/hr)

Location	^{18}F	^{15}O
E	1.1 (0.11)	4–12 (0.4–1.2)
F	0.6 (0.06)	4–20 (0.4–2.0)
G	0.4 (0.04)	0.4–1 (0.04–0.1)

these quantitative studies were at least twice as high as during studies where no blood samples were obtained (*8*).

PROCEDURES TO REDUCE EXPOSURES

Using shielding, working at the maximum practical distance and working for the minimum practical time are ways to reduce exposure from any source of ionizing radiation. Placing an intravenous line before radiopharmaceutical administration allows the technologist to rapidly inject the radiotracer and reduces the time of exposure for both positron-emitting and single-photon emitting radionuclides. Described below are additional procedures that can be implemented to reduce exposures from positron-emitting sources.

Based on the values shown in Table 1, we constructed an acrylic syringe shield with a wall thickness of 6 mm (Fig. 3). This has sufficient density to absorb all the mean energies ($\bar{E}_\beta$) of the positron emitters shown in Table 1 as well as the maximum energy (E_{max}) positrons of ^{18}F, ^{11}C and ^{13}N. The effects of the positron shield that we constructed are shown in Table 6. We saw a significant reduction in intensity from the ^{15}O source, as most of these positrons were able to penetrate the syringe wall but could not penetrate the wall of the plastic syringe shield.

Cataract formation is a nonstochastic event that means it is dose dependent and, as such, has a threshold. The threshold for this event is 200–500 rad for a single exposure and goes up to approximately 500–800 rad when the exposure is a lower dose and distributed over a period of time (*9*). The maximum permissible dose to the lens of the eye is 15 rad. To ensure protection of the lens of the eye from the maximum-energy ^{15}O positrons, we require our staff to wear industrial safety goggles (Fig. 3), which provide an additional millimeter of protection to absorb any remaining ^{15}O positrons.

TABLE 5
Radiation Exposure per ^{15}O-Water Cognitive Function Study

Location	Task	μSv (mrem)
A	Injecting radiotracer	160 (16)
B	Testing	80 (8)
C	Timing	40 (4)
D	Drawing blood samples	330 (33)

TABLE 6
Effects of the University of Chicago Positron Shield mGy/hr/MBq (mR/hr/mCi)

	^{18}F	^{15}O
Without shield	118.3 (169)	529.9 (757)
With shield	93.1 (133)	105 (150)

Using a 15-mm thick acrylic syringe shield and 50 mm of lead shielding around the injection site, Dachille et al. (*10*) reported they were able to reduce whole-body exposure from 0.014 mSv/MBq (0.02 mrem/mCi) ^{15}O water injected to 0.0014 mSv/MBq (0.002 mrem/mCi).

Reducing the exposure from 511-keV gamma photons may be the most difficult problem to solve in positron tomography studies. As shown in Table 2, a thickness increase of more than 12 times, using lead or tungsten, is required to provide the same level of shielding for 511-keV annihilation photons as for the 140-keV photons of ^{99m}Tc. To reduce the radiation intensity measured in an adjacent room from a ^{18}F source to the same level as a ^{99m}Tc source will require approximately 3/8 inch of lead. The lead pig shown in Figure 4, which provides just three half-value layers of shielding for ^{99m}Tc, would weigh over 50 lb if it were to provide the same degree of shielding for ^{18}F. Likewise, the tungsten alloy syringe shield, also shown in Figure 4, which provides approximately seven half-value layers of shielding for ^{99m}Tc, would weigh over 4 lb to provide the same shielding for ^{18}F.

One way to reduce staff exposure during PET studies is to automate the radiopharmaceutical administration process. While there are currently no commercial devices available, a number of prototypical devices have been built (*11–14*). Richmond et al. (*15*) reported an 81% reduction in staff hand exposure from 0.83 mSv/MBq (1.189 mrem/mCi) to 0.16 mSv/MBq (0.229 mrem/mCi) using a system they built. Gaskill et al. (*16*) reported a 58% reduction in whole-body exposure from 0.0154 mSv/MBq (0.022 mrem/mCi) to 0.0063 mSv/MBq (0.009 mrem/mCi) using a device they constructed.

We are presently constructing a system with an integrated dose calibrator using 20–25-mm-thick tungsten. This amount of tungsten should absorb 98% of the gamma photons. While

FIGURE 3. The University of Chicago positron shield (left) and a pair of industrial safety goggles (right).

FIGURE 4. A tungsten syringe shield (left) and a standard lead pig (right).

tungsten is more expensive than lead, a tungsten shield will be significantly smaller, weigh slightly less and be more durable than a lead shield. In addition, a tungsten shield will avoid potential concerns related to lead toxicity.

CONCLUSION

Time, distance and shielding must be evaluated and optimized when designing a PET facility or when developing procedures using positron-emitting radionuclides, in order to keep radiation exposures as low as reasonably possible. Adequate shielding from the ionizing effects of positrons can be achieved with 1 cm of acrylic that is able to absorb all routinely-used positrons except for the maximum-energy positrons of ^{82}Rb. Adequate shielding from the 511-keV gamma photons also can be achieved, however, significantly more shielding is required than for the photons of ^{99m}Tc.

Because of the higher energy of the positron and the often larger administered dose, centers considering using ^{82}Rb as their primary radionuclide should be prepared to deal with radiation levels in excess of what has been measured for ^{18}F and, depending on the patient volume, may have to deal with levels in excess of what has been reported for ^{15}O. Time, distance and shielding must be optimized when designing the PET facility and when developing PET procedures in order to keep radiation exposures as low as reasonably achievable.

PET studies require additional radiation protection precautions than studies with single-photon emitting radionuclides because of the ionizing potential of positrons and the high energy of gamma photons. If these precautions are not followed, exposures may exceed regulatory limits.

REFERENCES

1. Bloe F, Williams A. Personnel monitoring observations. *J Nucl Med Technol* 1995;23:82–86.
2. U.S. Department of Health, Education and Welfare. Public Health Service. *Radiological health handbook*. Washington, D.C.: Government Printing Office; 1970.
3. Brown TF, Yasillo NJ, Kronmal SL, et al. Radiation safety considerations in a positron tomography center [Abstract]. *J Nucl Med Technol* 1994;22:115.
4. Hicks K, Ganti G, Mullani N, et al. Automated quantitation of three-dimensional cardiac positron emission tomography for routine clinical use. *J Nucl Med* 1989;30:1787–1797.
5. Kearfott KJ, Carey JE, Clemenshaw MN, et al. Radiation protection design for a clinical positron emission tomography imaging suite. *Health Phys* 1992;63:581–589.
6. Metz J, Singh J, Gabrieli JDE, et al. Regional cerebral blood flow during acquisition of a procedural memory [Abstract]. *Society for Neuroscience Abstracts* 1993;19:1001.
7. Phelps ME, Huang SC, Hoffman EJ, et al. Tomographic measurement of local cerebral glucose metabolic rate in humans with [^{18}F]2-fluoro-2-deoxy-D-glucose: validation of method. *Ann Neurol* 1979;6:371–388.
8. McCormick VA, Miklos JA. Radiation dose to positron emission tomography technologists during quantitative versus qualitative studies. *J Nucl Med* 1993;34:769–772.
9. Lipman RM, Tripathi BJ, Tripathi RC. Cataracts induced by microwave and ionizing radiation [Review]. *Surv Ophthalmol* 1988;33:200–210.
10. Dachille MA, Milko JA, Ruszkiewicz JA, et al. Techniques to lower radiation exposure to PET personnel when performing multiple intravenous ^{15}O water injections [Abstract]. *J Nucl Med Technol* 1995;23:122.
11. Hichwa BD, Johnston DJ, Ponto LL, et al. Handheld automated injector for ^{15}O water studies [Abstract]. *J Nucl Med* 1991;32:1063.
12. Bandy DJ. An infusion system to administer short-lived radiopharmaceuticals used in positron emission tomography [Masters thesis]. Phoenix, AZ: Arizona State University; 1992.
13. Hichwa RD, Richmond JCW, Koeppel JA, et al. A simple dispensing/injection system for PET. [Abstract]. *J Nucl Med* 1994;35:188P.
14. Ruszkiewicz JA, Simpson NR, Milko DL, et al. Automatic [^{15}O] water synthesis and administration unit for multiple intravenous injection [Abstract]. *J Nucl Med Technol* 1996;24:163.
15. Richmond JCW, Hichwa BD, Watkins GL. Hand exposures from PET radiopharmaceuticals can be reduced easily and economically [Abstract]. *J Nucl Med Technol* 1992;20:105.
16. Gaskill M, McCormick V, Kondas D, et al. Reducing radiation exposure by utilizing a new injection device. *J Nucl Med Technol* 1995;23:122–123.