Site Planning and Radiation Safety in the PET Facility

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Scope

With the recent advent of readily available tracer isotopes from regional cyclotrons and a change in the reimbursement practice of insurance providers, there has been marked increase in the number hospital-based and free-standing positron emission tomography (PET) clinics. At the same time, the successful development of dual PET and x-ray computed tomography (CT) scanners has sparked an interest and appreciation of PET scanning that is also driving an increase in demand for new facilities. This paper addresses issues related to the design of such centers and the implementation of safe operating practices for handling PET isotopes. It will be restricted, in general, to the treatment of dedicated, full-ring PET and PET/CT scanners in the setting of specialized clinics and to the use of relatively long-lived ($T_{1/2}$=110 min) ^{18}F fluorodeoxyglucose (FDG). Cyclotrons and their shielding will not be discussed, nor will the operation of a radiopharmacy. However, the techniques discussed here can be applied to other situations by compensating for different workloads, amounts of injected isotope, choice of isotope, and other operating parameters.

Basic Concepts

Equipment for Positron Emission Tomography

Positron emission tomography is based on the characteristic way in which positrons annihilate by combining with an electron. This process usually results in the emission of two 511 keV photons that are very nearly collinear, but which travel in opposite directions. A PET scanner consists of an array of detectors that are arranged to detect the essentially simultaneous arrival of these two photons. The point of photon emission can then be taken to lie somewhere on the line connecting the two detectors which registered photon hits. After enough events are collected, reconstruction by either filtered backprojection or algebraic means results in an image of the distribution of the positron-emitting isotope. An image reconstructed strictly with the emission data and without further correction will exhibit artifacts due to attenuation and scattering in the body. To obtain information needed to compensate for these processes, a second scan will be taken in transmission mode to produce an image that is analogous to one obtained in a CT scan. The transmission scan can be made using either isotopes -- typically ^{68}Ge -- or an x-ray tube as the photon source.

At this time, modern types of equipment include hybrid cameras, partial ring scanners, fixed full-ring scanners, and PET/CT scanners. The type of equipment installed will determine the amount of radioactive material administered, the duration of the scan and the total workload for a room. Hybrid cameras are multi-head, NaI(Tl)-based gamma cameras that have been equipped with coincidence circuitry to allow PET acquisition. Their large axial field of view and limited count-rate capabilities typically restrict the amount of isotope that can be used. Dedicated scanners employ specialized detectors and coincidence circuitry that have been optimized for PET scans. Most of these devices place detectors in a complete circle around the volume to be imaged, but a few employ a partial ring of detectors that are then rotated around the subject in order to obtain all of the needed projections. The axial extent of most modern dedicated scanners is about 15 cm. Scintillation crystals in dedicated scanners are usually bismuth germanate (BGO), but newer materials such as LSO (lutetium oxyorthosilicate) and GSO (germanium oxyorthosilicate) are being used. LSO has a higher light output per photon interaction than BGO, allowing

scan times to be reduced while maintaining a constant noise figure for the image. PET/CT scanners are the current high-end devices for PET studies and combine a diagnostic-grade CT scanner with a dedicated PET machine in the same housing. This allows automatic registration of the physiologically determined PET image with anatomical information in the CT image. The attenuation and scatter corrections are based on an attenuation map generated from the CT image.

Facility Design

Workflow

Currently, the most common type of PET exam in clinical practice is an ^{18}F FDG scan of the whole body for oncology studies. Whole body scans may truly encompass the whole body, as is done in the case of melanoma studies, or may image the body only from the base of the brain to mid-thigh, which is the usual practice for non-Hodgkin's lymphoma, colorectal cancer, lung cancer, and head-and-neck cancers. This presentation will concentrate on site planning for a facility that performs whole-body FDG scans as its principal business, rather than those that do significant numbers of cardiac or brain studies or that work with shorter-lived isotopes such as ^{15}O ($T_{1/2}$= 122 s) or ^{82}Rb ($T_{1/2}$=75s).

The workflow for all of these scans is essentially the same. FDG will be received from the radiopharmacy either in a bulk vial or in a syringe as a prepared unit dose. The amount of activity required for injection may range from 110 MBq (3 mCi) to 560 MBq (15 mCi) or more, depending on the study to be performed and the type of scanner in use. After the syringe has been drawn or supplied as a unit dose, it will be checked in the dose calibrator and held in a shielded container until use. The patient, who should be in a fasting state, will be placed in an injection room and informed regarding the procedure that he will undergo. Depending on the patient's clothing and the planned exam, the patient may be asked to gown instead of wearing his street clothes. At this time his glucose level will be checked and, if it is found to be within acceptable limits (typically < 200 mg/dL), the injection will be performed. Although various approaches are employed for administration, a common technique is to use a butterfly infusion set that has been inserted in the vein prior to injection.

After injection, the patient will be held for 30-60 minutes to allow for pharmaceutical uptake.[1] During this time she should be in a quiet, darkened area, particularly if a brain scan is planned. The patient should be placed either in a comfortable chair that provides support to the arms, shoulders and head or else on a couch. Because active muscles take up FDG, failure to provide support may result in anomalous uptake in the muscles of the shoulders and neck. In our practice, the patient is placed on a gurney. At the end of the uptake period, the patient is urged to urinate in order to reduce the amount of activity in the bladder. She is then escorted to the exam room and positioned in the scanner. If the patient was not gowned, she may be asked to remove belts, metal jewelry, and so forth. What happens next depends on the type of hardware (conventional PET or PET/CT) that is used.

For dedicated PET, the patient will undergo emission scans and transmission scans. Emission scans are the PET scans proper. Transmission scans are run to derive an attenuation map that can be used to correct the PET scan for photon absorption. They are obtained by using isotopic line sources that orbit the patient. The resulting image has the appearance of a rather poor CT scan. Because the axial field of view of most dedicated PET scanners is limited to about 15 cm, complete scans are taken in a number of discrete bed steps. Each of these steps will typically take 7-8 minutes for a BGO scanner, with the time being split such that 30% of it is used for the transmission scan and 70% for the emission scan. Thus, a whole body 2D scan may require 6 beds and take about 50 minutes. A brain scan with the same equipment may take about 15 minutes.

In the case of PET/CT, the CT scan can be used with appropriate corrections to generate the attenuation map. Thus, the transmission scan is reduced from 30% of the total scan time to approximately one minute. The emission scan time remains commensurate with that required in conventional PET. At the conclusion of the exam, the patient remains on the couch until the technologist has checked the scan for artifacts and is then released from the clinic.

PET studies are often read from soft copy, particularly for PET/CT studies. After the technologist has checked the images, they will be sent to the reading room workstations. For PET/CT scanners, the CT images may need to be sent to separate reading rooms in the radiology department. Most of the printing needs at the facility are to produce hard copies of images selected by the physician for the patient's folder and for the referring physician.

Estimating the Workload

From the discussion above, it is clear that the maximum workload during a shift is determined by the choice of scanners employed in the center and the types of exams--whole body or brain scans--being conducted. If patient transport, positioning, in-room preparation, and image quality assurance are estimated to take a total of 10 minutes, whole body scans on BGO-based conventional PET machines will require one hour and brain scans about 25 minutes in the scanner bay. The use of BGO-based PET/CT will drop this to 40 minutes and 20 minutes. Employing LSO-based scanners will result in smaller times, about 40 minutes in the room for whole bodies with conventional PET and 30 minutes for PET/CT. Thus, for a center that performs whole-body studies with conventional BGO PET, a reasonable throughput for a scanner is 7-8 patients per day without running an extended shift. PET/CT can extend this to 10-16 patients per day. Although current technical improvements are reducing the scan times below those indicated here, this will not necessarily significantly increase the patient throughput. For example, CT exams typically take only a few minutes of actual scan time, but machine throughputs are usually limited to 3 or 4 exams per hour. Parameters for estimating the patient workload of a facility are summarized in Table I.

Table I. Approximate workload parameters for PET scanners performing whole body scans. Time per patient in the scanner bay is based on 10 minutes total additional time to perform QA on the scan and to transport and position the patient. Variations in injected activity and suggested scan time will occur between instrument models and the vendor should be consulted for specific values.

	Conventional, BGO	Conventional, LSO	PET/CT, BGO	PET/CT, LSO
Injected Activity, Whole Body [MBq (mCi)]	444 (12)	555 (15)	370 (10)	555 (15)
Scan Time Whole Body [min]	48	30	31	19
Time per Patient in Scanner Bay [min]	58	40	41	29
Patients/day (9 hour day)	8	12	12	16

Waiting Rooms

At full load, there will be a maximum of about 3 patients per scanner at the center at a given time if whole body scans are being done. Thus, the waiting room requirements are relatively modest. The waiting room should not be considered to be an appropriate setting for the uptake phase of the study. Not only is patient seclusion desired to obtain high quality scans, as noted above, but also the patient represents a relatively potent radiation source immediately after injection. This will be discussed later.

Hot Lab and Injection Rooms

The maximum number of injection/holding areas needed for every scanner is given by the ratio of the uptake time to the scan time. Thus, only one injection room per scanner is needed for doing whole body scans with conventional BGO-based PET. Two injection areas per scanner should provide ample capacity

for a PET/CT scanner with current capabilities. A toilet dedicated for patient use should be placed close to the injection areas so that the subject can empty his bladder prior to being escorted to the scanner. Privacy curtains, subdued lighting, and noise control should be provided.

The hot lab has few special requirements, particularly if unit doses are employed. Because the shielding requirements for 511 keV L-Blocks, sharps disposal, and dose calibrators are substantial, the benchwork needs to be quite solidly built. If unit doses are used, enough floor space needs to be allocated to store the isotope shipping carriers for the day's work. These are fairly bulky. One vendor's containers are approximately 20 cm x 25 cm x 32 cm (8" x 10" x 13") and weigh about 30 kg (66 lbs) each.

Because the doses are stored and handled with high initial activities and because the patients will contain the highest activities during the uptake phase, radiation exposures inside and adjacent to this area need to be carefully considered. With the exception of PET/CT scanning rooms, the injection rooms and hot lab are the areas that are most likely to require additional radiation shielding.

Scanner Rooms and Control Rooms

The minimum requirements for space in the scan rooms should be obtained from the vendor's site planning document. Representative dimensions for PET/CT scan rooms are given in Table II. Means of observing the patient and maintaining aural communications with the patient should be provided. If PET/CT is to be installed, wiring provisions should be made for a power injector.

Because the light output of BGO is temperature dependent, there are strict requirements for environmental control in the scan rooms. A thorough review of the heating, ventilating and air conditioning (HVAC) requirements for the purchased scanner should be made. Some scanners are equipped with thermal cutout switches that will automatically shut the system down if the room temperature exceeds specified limits. An extra effort should be made to communicate with the HVAC engineer and to make these requirements plain to him.

The control room should provide direct access to the scanner bays and have an uncomplicated traffic pattern to reach the hot lab and injection areas. Most of the technologist's time will be spent in the control room, so the radiation exposure to this area from the scanners, hot lab, and injection rooms should be carefully evaluated. The control area will also have considerable heat load from the acquisition and display computers. It may be desirable to have a HIS/RIS terminal in this area as well as a computer with connections to the departmental server, email system, etc. A generous supply of network drops should be provided in the control room. In the current networking environment, it is an unlikely scenario to have too many network drops in the control room, work area, or reading room.

Utility Rooms

Scanners provided by some vendors exhaust gantry heat into the scan room, while others have internal heat exchangers and use liquid cooling loops to maintain the temperature of the detector assemblies. The cooling loops can either be connected to the building chilled water system or to small refrigeration systems that exhaust the heat into room air. These refrigeration systems and electrical power conditioning equipment for the scanner are usually placed in a small utility room. Some systems may require separate space for electrical equipment associated with the x-ray generator of a PET/CT system. The air conditioning system for this room must be sized to handle all of the electrical loads known to be placed here and should have some reserve capacity above and beyond this.

Table II. Examples of approximate minimum room dimensions required for PET imaging equipment. Room sizes should be verified with the specific vendor of the equipment being installed.

Vendor/Equipment	Scanner Room [m] ([ft])	Control Room [m] ([ft])	Utility Room [m] ([ft])
Siemens/CTI HR+ Dedicated PET[2]	5.06 x 7.54 (16.6 x 24.8)	3.17 x 5.06 (10.4 x 16.6)	1.83 x 1.83 (6 x 6)
Siemens/CTI Biograph/Reveal PET/CT[3]	5.03 x 7.50 (16.5 x 24.8)	3.18 x 5.03 (10.4 x 16.5)	1.83 x 1.83 (6 x 6)
GE Advance Dedicated PET[4]	3.97 x 5.96 (13 x 19)	3.35 x 3.82 (11 x 12.5)	2.14 x 3.35 (7 x 11)
GE Discovery LS PET/CT[5]	3.87 x 7.00 (12.7 x 23)	2.50 x 3.87 (8.2 x 12.7)	1.3 x 3.87 (4.3 x 12.7)

Technologist's Work Area (Printer and File Area)

As noted above, the hardcopy requirements for most PET facilities will be limited to printing representative images for documentation and for distribution to the referring physicians. If PET/CT will be employed, printers with color capability should be available to print black-and-white anatomical images with color overlays showing the PET information.

Reading Room

Almost all PET reading is done from softcopy on workstations. Some limited number of light boxes should be provided for existing studies that are on film. Adequate space, power, telephone lines, network drops and air conditioning should be provided to support the special purpose reading stations associated with the PET or PET/CT, a HIS/RIS workstation, a PACS workstation, and the dictation system. Since PET is likely to remain an important modality in research protocols, separate workstations for image manipulation and data analysis may be desirable in this area. Adjustable, indirect lighting should be provided.

Miscellaneous Pragmatic Advice

If possible, build the hot labs, injection rooms, and scanning rooms in the interior part of the available space, away from walls with adjacent, uncontrolled occupancies. This may obviate the need for shielding around some or all of the areas.

If new construction is being planned, make provision for PET/CT scanners, since it is probable that these scanners will soon become the standard of practice.

If multiple scan rooms are being built, employ a combined control room that will allow a single technologist to keep more than one room under observation at the same time. Even with PET/CT, there is a significant amount of PET acquisition time required for a whole body scan, during which the technologist can be performing other work.

Anecdotally, inadequate air conditioning is one of the most common problems encountered in starting up a new center. Make sure that the HVAC engineer understands the requirements. It is advisable that dedicated air conditioning systems be put in place for both the scanner bay and the electronics/utility rooms, if they are present. Making an independent set of heat load calculations is advisable.

The specialized software needed for reading both conventional PET and PET/CT makes it impractical to read from many general-purpose PACS stations at the present time. Either dedicated PET workstations or special nuclear medicine workstations are required. This means that workstation resources can be overloaded as technologists, physicians, and researchers compete for time on the stations. Acquiring additional workstation capacity at the time the system is purchased is recommended.

Radiation Protection in PET Facilities

Special Aspects of PET Facilities

In the past, shielding was often unnecessary in Nuclear Medicine departments performing only diagnostic studies. PET facilities differ from normal departments in that the studies employ relatively large activities of high-energy photon emitting isotopes and may also use equipment that has CT scanning capability. This, coupled with the current dose limits for members of the public, can result in a shielding requirement. Because even modest dose reductions at 511 keV require significant amounts of shielding, a thorough and site-specific evaluation should be made for each facility.

Radiation Protection Goals

The radiation protection goal for members of the public, established by the Nuclear Regulatory Commission and mirrored by state regulations in agreement states, is to limit exposure to insure that no individual will be receive more than 100 mrem/year (1 mSv/year) total effective dose equivalent from the licensed operation.[6] On a weekly basis, this means controlling dose to the level of 2 mrem. This is approximately 30% of the mean effective dose rate from natural background radiation in the United States. There is an additional requirement that the dose rate in areas accessible to members of the public not exceed 2 mrem in any given hour (.02 mSv/hour). Institutional staff members whose assigned duties do not involve exposure to radiation sources are considered to be members of the public.

Radiation workers are limited to receiving 5000 mrem (50 mSv) total effective dose equivalent per year.[7] In additional, there are dose limits to individual organs (50 rem or 500 mSv per year), extremities and the skin (50 rem or 500 mSv per year), and the lens of the eye (15 rem or 150 mSv per year). The dose to the fetus of a radiation worker who declares herself to be pregnant is limited to no more than 500 mrem (5 mSv) in the course of the pregnancy as a consequence of occupational exposure to the mother.[8] Operationally, this last requirement is usually implemented by a monthly limitation of 50 mrem (0.5 mSv) to the fetus.

In addition to the specific limitations outlined above, each licensee has an obligation to conduct operations so as to maintain doses to both radiation workers and to members of the public as low as reasonably achievable (ALARA).

Isotope Parameters

All PET isotopes give rise to two 511 keV photons per emitted positron. In addition, there can be additional gamma rays from the nuclear decay and bremsstrahlung radiation emitted as the positron slows down. ^{18}F decays by positron decay 96.9% of the time, with the balance of decays occurring by electron capture. ^{15}O, ^{11}C and ^{13}N all decay by positron decay with essentially unit probability. Bremsstrahlung production is strongly dependent on the atomic number of the medium in which the positron travels and on the positron energy. It will be strongly curtailed in low Z materials such as water and soft tissues. ^{18}F has the lowest positron energy of the common PET isotopes and therefore, under fixed conditions, will have the lowest amount of bremsstrahlung radiation. ^{82}Rb has the highest positron energy (3.15 MeV) and also is the only isotope to have significant contamination from other gamma rays (approximately 9% at 777 keV). ^{82}Rb also differs from the other isotopes in that it is generator-produced from its parent ^{82}Sr. The ^{82}Sr-^{82}Rb generator represents another radiation source that must be included in the shielding evaluation. The decay

parameters and gamma ray dose constants for the most widely used positron sources are summarized in Table III.

Table III. Decay parameters for isotopes commonly used in PET scanning. ^{68}Ge is included because it is used for PET calibration sources. It decays by electron capture with a 100% branching ratio to ^{68}Ga (half-life = 68 minutes), the positron emitter. Half-life, annihilation photon intensity, and positron energy are from Lederer and Shirley.[9] The specific gamma-ray dose constants are those of Unger and Trubey (ORNL/RSIC-45, 1981), as given by Shleien *et al.*[10]

Isotope	Half-Life [min]	Annihilation Photon (511 keV) Intensity per Decay [%]	Positron Energy [MeV]	Gamma-Ray Dose Constant [(μSv/hr)/MBq] ([(mrem/hr)/mCi]) at 1 meter
^{11}C	20.38	200	0.961	0.194 (0.717)
^{13}N	9.97	200	1.19	0.194 (0.171)
^{15}O	2.03	200	1.72	0.194 (0.717)
^{18}F	109.7	194	0.635	0.188 (0.695)
^{68}Ge-^{68}Ga	4.1e5 (288 days)	180	1.9, 0.8	0.179 (0.662)
^{82}Rb	1.25	192	3.35,2.57	0.210 (0.778)

Shielding Material Properties

Lead and concrete are the most likely materials to be used for area shielding in the PET facility. The attenuation factor necessary for shielding is likely to be no more than 10, but the high penetration of 511 keV photons can require a significant thickness of either material.

Lead is readily available in the form of leaded wallboard and as plate and sheet stock for special construction. Under narrow beam conditions, it has a mass attenuation coefficient of 0.153 cm^2/g and a half value layer of 3.98 mm at 511 keV. The effective half-value layer of lead for shielding photons of this energy under broad beam conditions has been reported in the range 4.1-5.5 mm.[10,11,12] More precise calculations can be made either by using build-up factors or transport codes. In a build-up model, the transmitted radiation intensity through a barrier, I, is given by

$$I = I_o B(\mu x) e^{-\mu x}$$

where I_o is the incident intensity, $B(\mu x)$ is the build-up function, μ is the linear attenuation coefficient of the shield, and x is the thickness of the shield. The appropriate build-up function for the shield geometry should be used.

Concrete has a mass attenuation coefficient of 0.0877 cm^2/g and a half value layer of 3.4-4.3 cm under narrow beam conditions at 511 keV. The range in half value layer given here corresponds to the difference between normal density concrete (2.35 g/cm^3) and low density concrete (1.84 g/cm^3) that is commonly used in modern construction for poured-in-place floors over steel decking. The build-up in concrete is more

significant than that in lead and, again, either build-up factors or transport codes can be used for more precise calculations. Narrow beam attenuation half value layers for lead and concrete are given in Table IV.

Courtney et al.[11] evaluated gypsum wallboard as a shielding material at 511 keV, but found it to have a transmission factor of 91% even at a thickness of 11.4 cm. Thus, wallboard normally makes a negligible contribution to shielding in the facility.

Table IV. Comparison of half value layers for different shielding materials at 511 keV under narrow beam conditions.

Material (density in [g/cm^3])	Half-Value Layer at 511 keV Narrow Beam Conditions [mm]
Lead (11.4 g/cm^3)	3.98
Concrete (2.35 g/cm^3)	34
Concrete (1.84 g/cm^3)	43

The standard reference for practical shielding design is *Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV, NCRP Report No. 49*.[13] Unfortunately, the attenuation charts given there (NCRP 49 Figs. 11 and 12) do not show data for 511 keV photons. However, curves are shown for the attenuation of ^{137}Cs photons (662 keV) in both concrete and lead. Use of these values will lead to a very conservative shielding plan. On the other hand, relatively small values of μx (the product of the linear attenuation coefficient and the shield thickness) are encountered in these problems. Under these conditions, the buildup factor does not vary tremendously with energy and the attenuation can be obtained to some degree of approximation from the NCRP 49 data by correcting for the change in linear attenuation coefficient between 662 keV and 511 keV. Note that the NCRP 49 curves for concrete are for material with a density of 2.35 g/cm^3 and would need adjustment for cases in which low-density concrete had been used.

Source Terms

The sources that must be considered in the shielding plan are the doses themselves prior to injection, calibration sources that are stored on the premises, the patient after injection, the transmission sources in the scanner and the scatter and leakage radiation from the CT scanner if PET/CT is used.

Point Sources

Shielding requirements for uninjected doses and for the calibration sources can be evaluated using the gamma-ray dose constants given above. A considerable amount of isotope may need to be held if a full schedule of patients is planned and deliveries from the radiopharmacy are limited. For example, if four patients are to be done in the course of a morning with an injected dose of 370 MBq (10 mCi) each but with only one delivery, then a single shipment received at 7 AM will consist of approximately 4200 MBq (113 mCi). Note that the doses are normally delivered in substantial shipping casks. The calibration sources, which might be on the order of 110 MBq of ^{68}Ge, are normally sold with their own storage pigs.

The Patient as a Source

Once the patient has been injected, they represent a source of radiation to the staff and members of the public. A number of studies have been made of the magnitude of this exposure from ^{18}F-FDG.[14,15,16,17,18] The results, at 1 m from the patient's anterior thorax and corrected for physical half-life to a common time, range from 0.055 to 0.150 (μSv/hr)/MBq (0.203 to 0.553 (mrem/hr)/mCi), as shown in Table V. For comparison, the corresponding dose rate given in NCRP 124[19] for a patient injected with ^{99m}Tc MDP is

about 0.0135 (μSv/hr)/MBq (0.05 (mrem/hr)/mCi) when measured 5 minutes after injection. Thus, the dose rate per unit activity from the patient undergoing the PET scan is larger by a factor of between 4 and 7. The variation in reported values for ^{18}F may be due both to measurement methodology and to different experimental conditions. For example, it is not stated in some of the studies whether the patient had emptied their bladder or not at the time of measurement. In other studies, that condition is specified. At one hour post injection, approximately 20% of the injected dose will have accumulated in the bladder,[20] and may have been eliminated. Data for dose rates measured from different surfaces of the body can also be found in several of these references, allowing a more realistic, non-isotropic model of the patient to be used.

Table V. Normalized dose rates at 1 m from the anterior surface of the patient. Originally reported values have been adjusted to a common time by correction for the physical half-life of ^{18}F. Values for Benetar are pre-void and those for Cronin are post-void. References to the sources are given in the text.

Source	Year	Dose Rate at 1 Meter [(μSv/hr)/MBq] ([(mrem/hr)/mCi])
Kearfott	1992	0.075 (0.279)
Chisea	1997	0.055 (0.203)
Cronin	1999	0.100 (0.370)
Benetar	2000	0.150 (0.553)
White	2000	0.137 (0.508)

Integral Sources

The scanner may use integral ^{68}Ge sources to obtain the transmission scans and to normalize and calibrate the detection system. As an example, in the Siemens/CTI EXACT machines there are 3 sources of nominal 111 MBq (3 mCi) activity. In the GE Discovery, two 370 MBq (10 mCi) and one 56 MBq (1.5 mCi) sources are used for calibration and normalization. The vendor can usually provide curves showing the isodose contours around the machine due to the use of the integral sources.

Shielding Calculations

Shielding calculations can conveniently be done either in a spreadsheet or with a mathematical modeling package. In outline, the sequence of steps proceeds just as in any other shielding problem:

- Obtain a scale drawing of the facility

- Determine the expected workloads of the facility in terms of number of patients examined per day, isotope activity used per patient, and CT workload (total mAs and kVp) per patient

- Determine the occupancies of areas within the facility and in adjacent, uncontrolled areas. Include consideration of occupancies above and below the facility in multifloor buildings. Use occupancy factors for uncontrolled areas, just as in x-ray calculations.

- Determine the location and initial activities of all isotopic sources to be considered in the calculation and the amount of time the source will be present. This includes the injected patient as a source.

- For both ^{18}F (half-life = 110 min) and ^{68}Ge (half-life = 288 days) sources, the activities must be integrated over the appropriate time periods to obtain the total dose delivered by the source.

- Obtain the isodose curves for the transmission sources in a PET scanner. Obtain the isodose curves for the CT section of a PET/CT scanner.

- Calculate the total dose from all sources at test points established at the principal work areas and at points in uncontrolled areas using the source strengths, source locations, workload factors, gamma-ray dose constants, and the inverse square law. When CT scatter is included, the data from NCRP Report No. 49 should be recast into barrier transmission for these calculations. Either spreadsheets or mathematical modeling packages can accommodate anisotropic sources in these calculations. If the calculated doses meet the protection criteria outline above, no shielding is required.

- If the protection criteria are not met, add shielding materials to barriers until they are.

In some cases, no shielding may be required or only shadow shields in the hot lab and injection areas may be needed. In other cases, more comprehensive shielding may be necessary. PET/CT suites will require, at a minimum, the shielding (including leaded control room windows) appropriate for the CT section of the scanner.

Radiation Safety Issues

Typical doses to technologists

McElroy[21] found that most of the dose received by the technologist occurs during the transport and positioning of the patient, followed by the preparation and assay of the dose. This is consistent with standard nuclear medicine practice.[19] A number of investigators have determined the whole body effective dose received by technologists per injected dose and per procedure.[15,17,21,22] Average values based these reports indicate that the technologist receives about 9.3 μSv (0.93 mrem) per procedure and 0.018 μSv/MBq (0.066 mrem/mCi) per unit injected activity. This is consistent with our own experience of 7.4 μSv (0.74 mrem) per procedure and 0.019 μSv/MBq (0.069 mrem/mCi) per unit injected activity. Extremity doses to the fingers can be substantial as a consequence of handling the syringe during assay and injection.

Special Equipment

Vendors are providing specialized equipment to reduce exposure to operating personnel in the PET center and to improve instrument performance in the higher radiation background found in the hot lab. This equipment includes:

- Dose calibrators with thick lead shielding to reduce operator exposure during the dose assay,

- Well counters with external shields to reduce background from stored doses, sources in the scanners, and calibration sources,

- Tungsten syringe shields to reduce finger dose during injection,

- Remotely actuated syringes that keep the syringe totally enclosed in a shield while the operator delivers the dose by pushing on an extension rod,

- Extra thick L-block table-top shields (5 cm of lead compared to 1.2 cm of lead in standard nuclear medicine applications) (note that such shields may weigh 250 kg compared to 60 kg for standard nuclear medicine models), and

- Syringe carriers and sharps containers with extra shielding.

Miscellaneous Operating Suggestions

Transporting and positioning the patient are the operations that deliver the most dose to the technologist. Maximize separation from the patient after injection and minimize the time spent with them. Patient instruction should be completed before injection, as should the completion of any forms or questionnaires. If the patient is ambulatory, allow as much separation as feasible when they are escorted to the scanner room. Minimize time spent near the patient in the scanner room.

Use of unit doses will reduce technologist exposure compared to the use of bulk distribution radiopharmaceuticals.

In laying out the hot lab, particular attention should be paid to minimize the time required to handle the dose during the assay and verification steps.

Establishing IV access with a butterfly infusion set before the dose is taken out of the shield can reduce handling time of the syringe.

Use of a cart to transport the dose from the hot lab to the injection room will increase the separation between the technologist and the syringe and reduce dose if the transport time is equivalent.

Release of radioactive patients

The short half-life of ^{18}F limits the dose that members of the public are likely to receive after release of the patient from the PET facility. The federal regulations governing the release of radioactive patients, 10CFR35.75[23], provide for the release of individuals if it is unlikely other members of the public will be exposed to more than 5 mSv (0.5 rem) as a consequence of this action. If other individuals are likely to be exposed to more than 1 mSv (0.1 rem), then the released patient must be provided with written instructions for conduct. Instructions are also required if the dose to a breast-feeding infant or child could exceed 1 mSv (0.1 rem). State regulations mirror these requirements. The implementation of this policy is discussed in Regulatory Guide 8.39 from the Nuclear Regulatory Commission,[24] which provides a formalism for calculating the doses at which these limits will be met. This guidance employs very conservative estimates in which the occupancy at 1 meter from the patient is assumed to be 100% for radionuclides with half-lives less than one day. Even under this assumption, the dose for release is on the order of 330 mCi, about twenty times that normally used for FDG studies. Hicks *et al.* have considered the dose delivered to breast-feeding infants after FDG exams.[25] Their conclusion is that it is unlikely that the internal dose due to ingesting radioactive milk will exceed the 1 mSv limit, even without a temporary cessation of breast-feeding. However, they also conclude that the external dose due to being held in proximity to the mother could be more significant. Their advice is that mothers who choose not to temporarily suspend breast-feeding while the FDG physically decays can minimize exposure to their infants by expressing the milk and allowing a third party to bottle-feed the infant during this period.

Conclusion

PET facilities present somewhat different design requirements than conventional nuclear medicine departments and are more likely to require additional radiation shielding. By use of appropriate design and by maintaining good operating practices, radiation doses to staff and the public can be kept to acceptable limits.

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