

Shielding of Medical Facilities. Shielding Design Considerations for PET-CT Facilities

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Abstract

The radiological evaluation of a Positron Emission Tomography (PET) facility consists of the assessment of the annual effective dose both to workers occupationally exposed, and to members of the public. This assessment takes into account the radionuclides involved, the facility features, the working procedures, the expected number of patients per year, and so on. The evaluation embraces the distributions of rooms, the thickness and physical material of walls, floors and ceilings. This work detail the methodology used for making the assessment of a PET facility design taking into account only radioprotection aspects. The assessment results must be compared to the design requirements established by national regulations in order to determine whether or not, the facility complies with those requirements, both for workers and for members of the public. The analysis presented is useful for both, facility designers and regulators. In addition, some guidelines for improving the shielding design and working procedures are presented in order to help facility designers' job.

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1. Introduction

1.1 Historical review

The first non-invasive technique to get images from the brain was a big revolution in itself. It was the radiography, invented in 1896, which used x-rays, discovered also by Wilhelm Röntgen. However, x-rays could show only the anatomical structures, and nothing else, i.e. it was an anatomical technique. The function of these structures could be inferred from anatomical changes, but only when they happened. In the early part of 1950, several suggestions were made in order to improve the quality of nuclear images for the detection of brain tumours and other brain diseases. In particular, it was suggested that the use of annihilation radiation following positron emission might improve the quality of brain images by increasing sensitivity and resolution. Finally, before the end of that year, the Physics Research Laboratory at Massachusetts General Hospital established a simple positron scanner using two opposed sodium iodide detectors. The results were encouraging. Data were obtained by translation of the two opposed detectors using coincidence detection with mechanical motion in two dimensions and a printing mechanism to form a two-dimensional image of the positron source. The success of the prototype positron scanner led to develop a scanner designed specifically for brain imaging^[1]. Figure 1 is a photograph of that first clinical positron imaging device at Massachusetts General Hospital (1953), and Figure 2 shows the corresponding scan of a patient with a recurring brain tumour. This PET scan resulted to be the first one in the world.

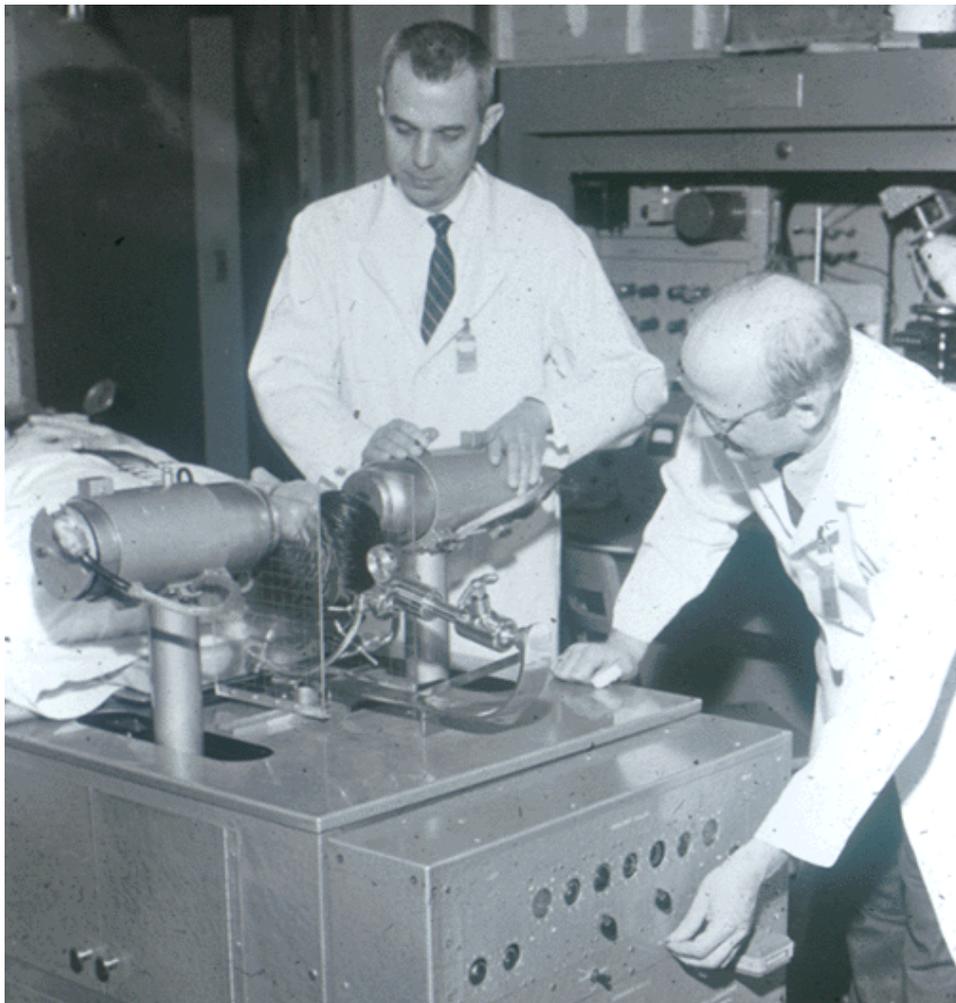


Figure 1. The first PET scanner in the Physics Research Laboratory at Massachusetts General Hospital (1953)

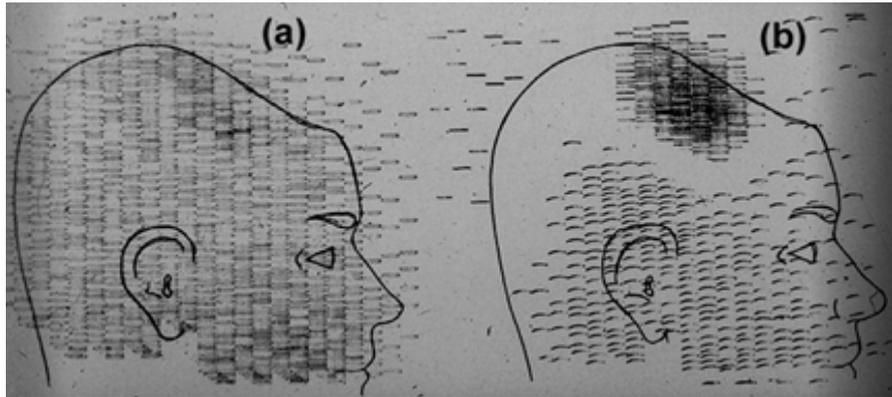


Figure 2. The first PET scan in the world (1953).

PET scanners developed parallel to technology during the following 50 years that came after the first development. Figure 3 shows the evolution of image quality from the first PET scanners to the latest and most sophisticated models^[2].

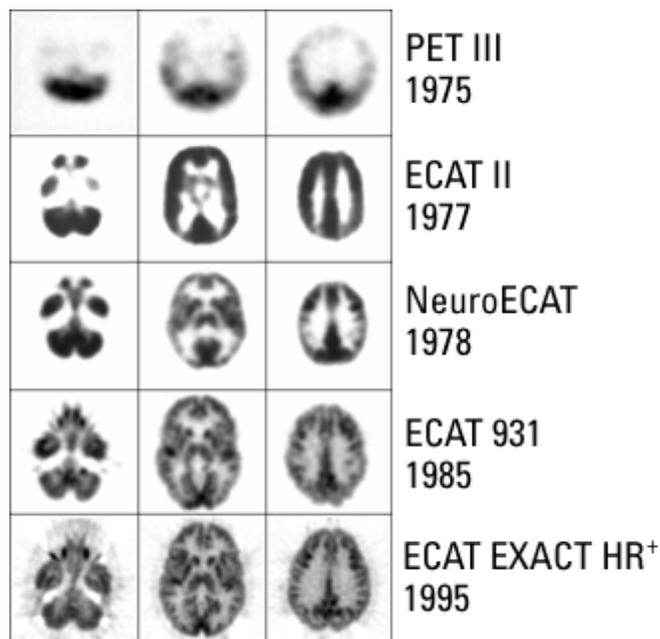


Figure 3. Evolution of image quality in PET scanners.

Modern PET scanners are very expensive sophisticated equipment. They are also much easier to install and to operate, with many new capabilities. PETs are so expensive that there are only about 150 installations around the world, which are mainly concentrated in USA, Europe and Japan. In the Southern Hemisphere, only Australia and Argentina have a very small number of PET facilities. Actually it's rather the whole facility, including the cyclotron for radiopharmaceuticals production, what push cost up^[2].

In some nuclear medicine centres, PET images are superimposed with computed tomography (CT) or magnetic resonance imaging (MRI) to produce special views, a practice

known as image fusion. These views allow the information from two different studies to be correlated and interpreted on one image, leading to more precise information and more accurate diagnoses (see Figure 4 for an example). In addition, manufacturers are now making PET/CT units, which are able to perform both imaging studies at the same time.

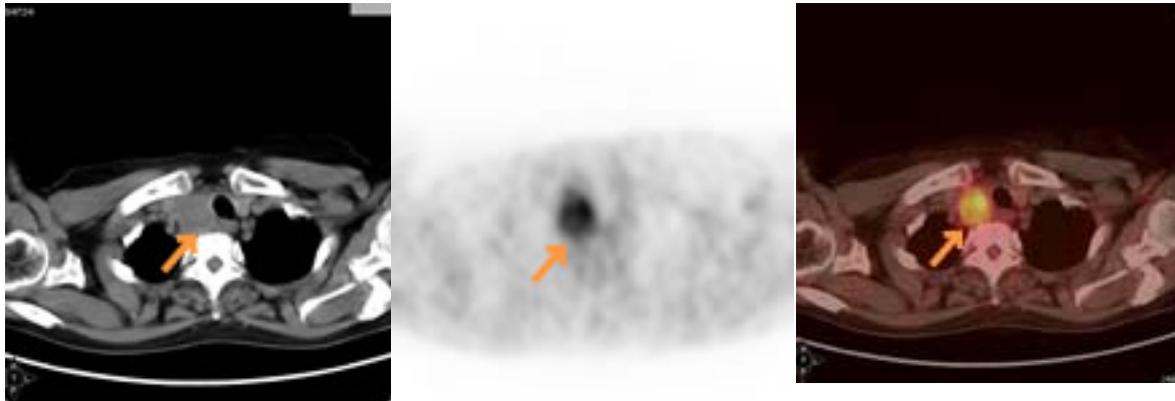


Figure 4. Example of image fusion at PET studies. Left: Detailed anatomy image from CT tomography. Centre: Image from PET study (no anatomy details present). Right: Image fusion of CT and PET images showing the tumour location into the detailed anatomy image.

1.2 PET at modern age

Positron emission tomography (PET) has been available worldwide for more than 23 years, but its use was not widespread until about 8 years ago. The power of PET resides in its ability to capture physiology and thereby obtain crucial diagnostic information unavailable from high-resolution pictures of the anatomy^[3]. This technique is a noninvasive diagnostic imaging tool that takes advantage of certain radiopharmaceuticals and allows abnormal metabolic activity in and around organs to be examined by injection of a radionuclide into a patient. As a result of the small chemical quantities administered to each patient, the radiopharmaceuticals do not disturb the physiologic processes of interest^[4].

Certain radionuclides decay by spontaneously converting a proton into a neutron and simultaneously emit an energetic positron (β plus decay). After the positron dissipates its kinetic energy as it traverses tissue (or other material), it captures an electron and forms a positronium atom. Because the electron and positron are antiparticles, they mutually annihilate, producing two 511 keV photons. The PET diagnostic technique is based on the detection of annihilation photons from a positron emitter radionuclide previously administered to a patient. Detectors positioned around the patient detect annihilation radiation resulting from the emitted positrons interacting with electrons. This annihilation radiation is released as two 511 keV photons that are emitted 180° apart. In the event that both of these photons are detected (gamma coincidence detection), the location of the annihilation interaction can be found using gamma detectors in a ring configuration. In Figure 5 can be seen an schematic of the complete detection system, while Figure 6 shows a real detector configuration used in commercial equipment. When the applications of PET and computed tomography (CT) are combined, a powerful diagnostic tool results: PET/CT. The PET portion provides molecular activity levels, while CT provides the anatomical structure of the body^[4]. The schematic for this system can be found in Figure 7.

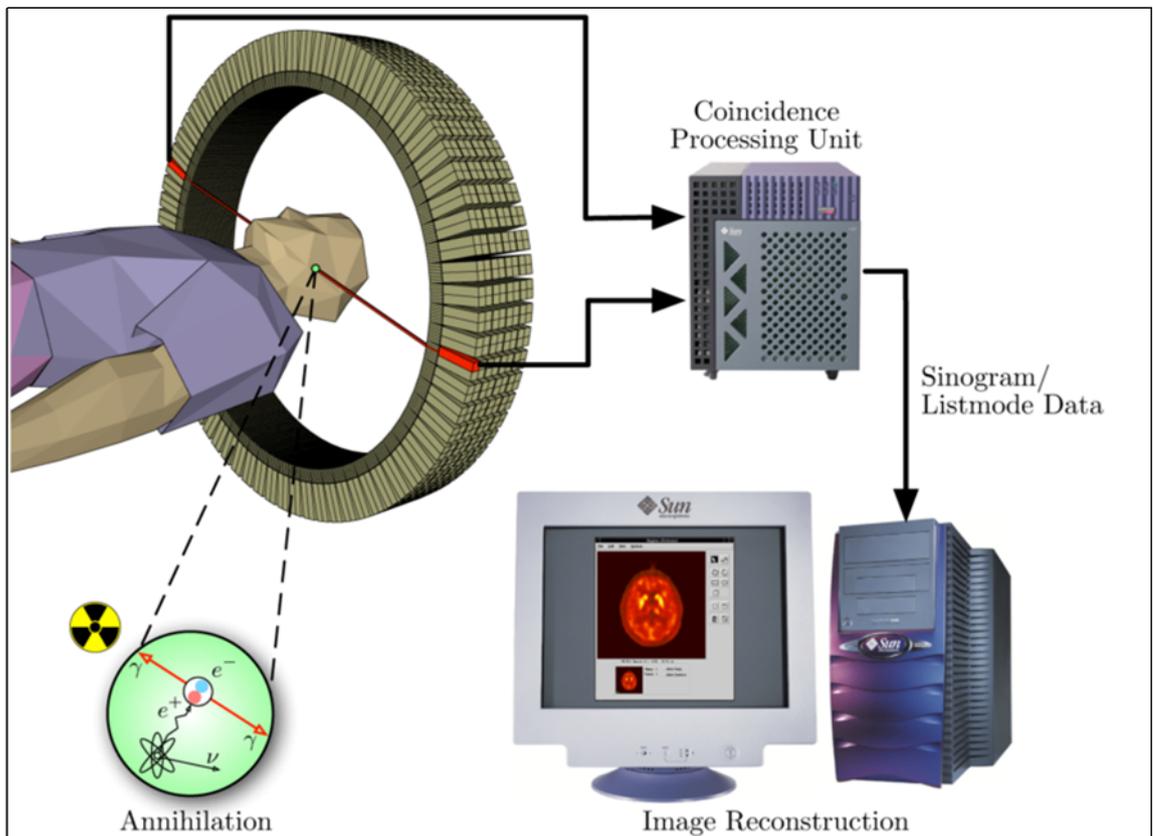


Figure 5. Schematic of the detection of scattered gammas in a PET scanner



A Siemens Ecat HR+ positron camera with front panel removed

Figure 6. Real detector configuration used in commercial equipment.

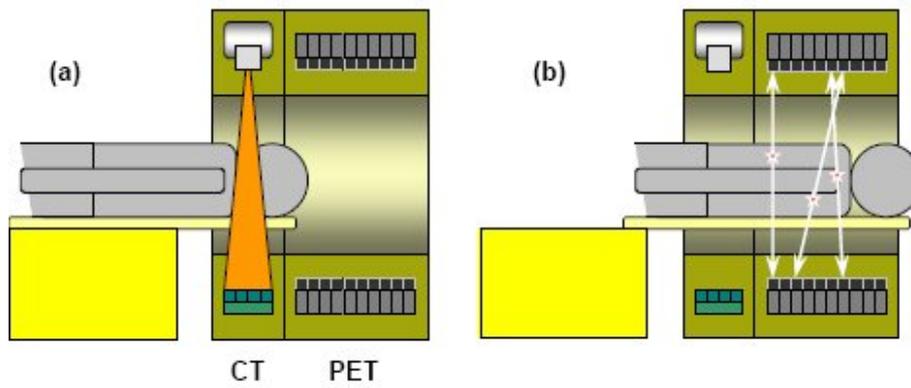


Figure7. Schematic of a PET/CT system

Figures 8a and 8b show a modern equipment which implements the PET/CT suite. The right picture in Figure 8b is the control room, with the modern computers that command the whole suite. The observation window is made of lead glass of thickness adequate for protection of operator from gamma radiation.

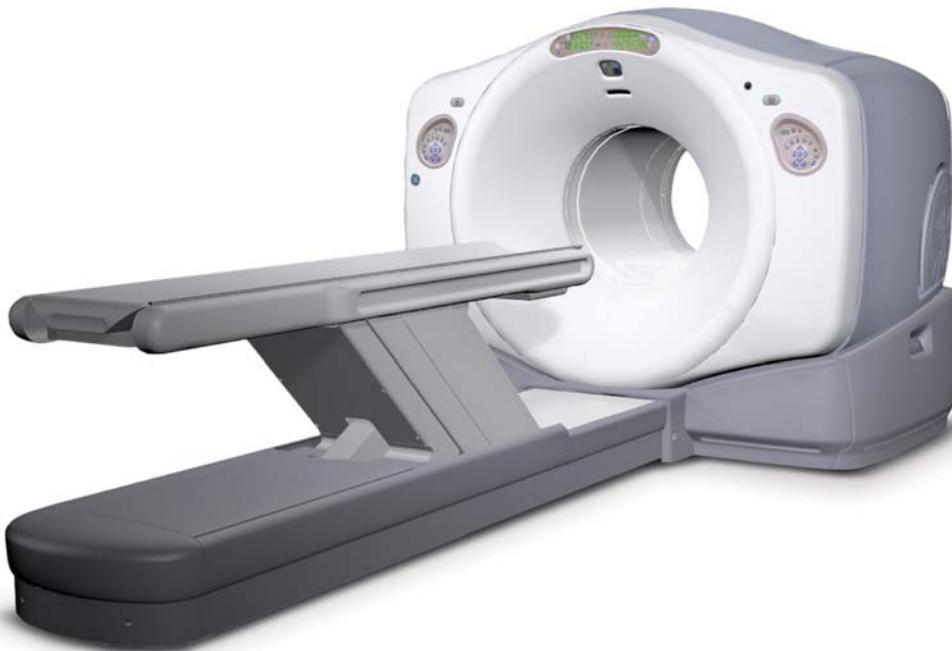


Figure 8a. Different views of a modern PET/CT suite

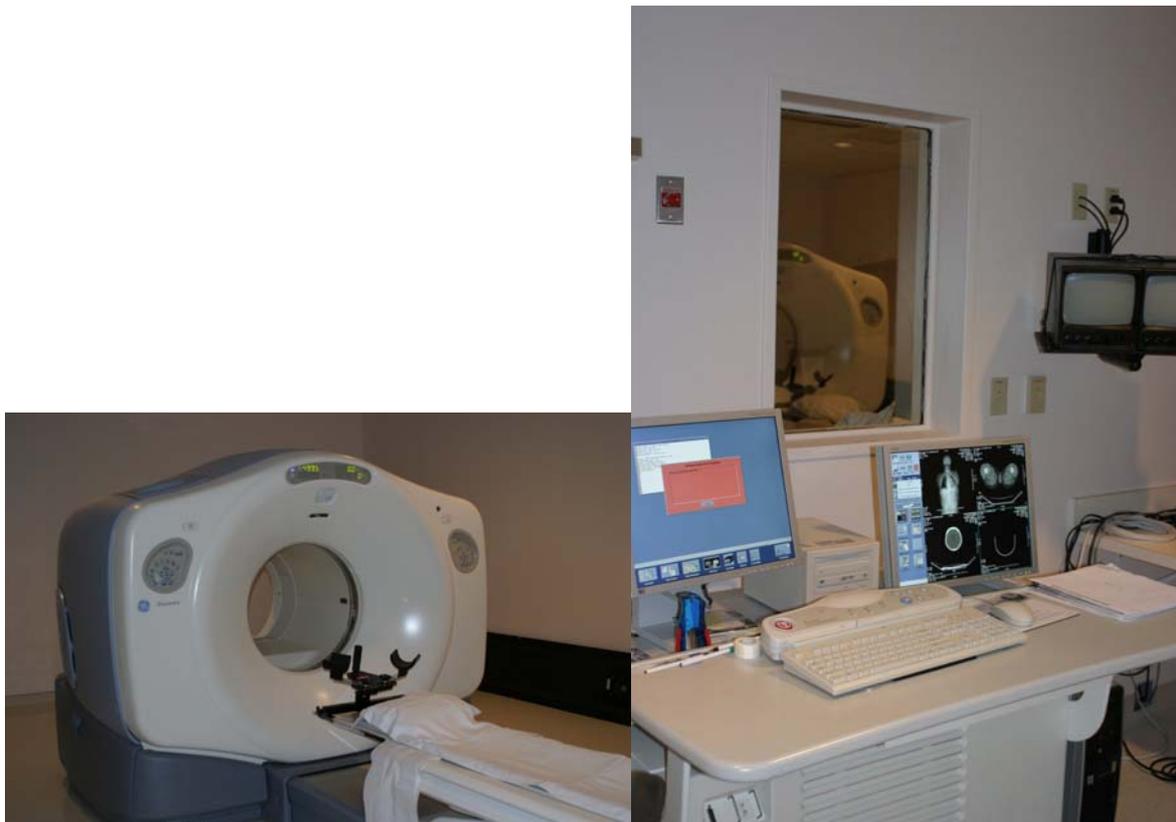


Figure 8b. Different views of a modern PET/CT suite

The recent explosion of interest in PET as a diagnostic imaging modality originates from mainly three factors: powerful radiotracers, coincidence detection technology, and study reimbursement^[3].

Being a diagnostic technique, the positron-emitting radionuclides more commonly used in PET (^{15}O , ^{13}N , ^{11}C and ^{18}F) have typically short half-lives and consequently many of them, such as ^{15}O , ^{13}N , and ^{11}C , have to be produced with an on-site cyclotron in order to have clinically useful quantities available (see Table 1 for more details). However, the 110 min half-life of ^{18}F is long enough to be regionally supplied.

The most versatile clinical PET radiopharmaceutical is F-18 Fluoro-2-deoxyglucose (F-18 FDG), a glucose analogue. F-18 FDG is accumulated in high concentration in metabolically active tumours as well as in the brain and the myocardium^[3]. A look at table 1 shows that ^{18}F has relatively longer half-life compared to the other commonly used positron-emitting radionuclides; on the other hand and foremost, ^{18}F is by far the most frequently radionuclide used in PET studies. Consequently, the expected radiation protection measures assuming that ^{18}F is always used should be adequate for studies where the same activity of shorter-lived radionuclides are applied. Because of this, this work focuses on PET centres that use ^{18}F .

Table 1: Dosimetric properties of commonly radionuclides used at PET.

Radionuclide	Energy [MeV]	Emissivity	Half-life
¹¹ C	0.511	2.00	20.4 min
¹³ N	0.511	2.00	10.0 min
¹⁵ O	0.511	2.00	2.0 min
¹⁸ F	0.511	1.93	109.8 min
⁶⁴ Cu	0.511 – 1.346	0.38 – 0.005	12.7 h
⁶⁸ Ga	0.511	1.84	68.3 min
⁸² Rb	0.511 – 0.776	1.90 – 0.13	76 s
¹²⁴ I	0.511 – 0.603 – 1.693	0.5 – 0.62 – 0.3	4.2 d

2. Evaluation procedure

In a typical practice, PET/CT patients are injected with an average activity of about 555 MBq (15 mCi) of F-18 FDG and instructed to lie down in what is called the uptake room for about 45-60 minutes while the radionuclide distributes throughout their body. They are then instructed to void their bladder of urine accumulation (in order to avoid signal interference due to gamma emission from bladder and also to reduce gamma dose in the bladder), and then taken to the scan room where they are given the approximately 20-30 minutes scan. By the time the patient leaves the PET/CT suite, the majority of the short-lived ¹⁸F (half-life is 110 minutes) has either voided from their body or physically decayed^[4]. Figure 9 shows a typical room layout used in nuclear medicine clinics. The shaded areas show the rooms specific to PET diagnostic: the hot lab (i.e. the place where all the radioactive sources are manipulated and stored until injection time), the uptake rooms (named “quiet” in this layout), the toilet exclusive to PET patients, and the scan room (PET/CT exam room in this case).

The radiological evaluation consists of the assessment of the annual effective dose to occupationally exposed workers and to members of the public. This evaluation takes into account the radionuclide involved, the characteristics and layout of the facilities, the working procedures and the expected number of patients per year. The evaluation embraces the distributions of rooms, the thickness and physical material of walls, floors and ceilings. The working procedures must give information of ¹⁸F activity administered per patient, the duration of time that each injected patient remains in the waiting room (uptake time), the duration of time of image acquisition (acquisition time), and so on. Occupational factors of the different areas are considered in the evaluation. Due to the characteristics of PET studies, the sources that are taken into account are: 1) radioactive sources in the hot lab, 2) the patient at rest during the uptake time, and 3) the patient in the PET scanner during the acquisition time.

Every PET facility must comply with the regulatory standards established in the country where the facility is located. These standards are mainly based on ICRP recommendations, the last being ICRP 103^[5]. These recommendations suggest the effective dose limits for planned exposure situations: 20 mSv per year for occupational exposure, and 1 mSv per year for public exposure. Similarly, the same recommendations suggest that every practice must be optimised: the likelihood of incurring exposures (where these are not certain to be received), the number of people exposed, and the magnitude of individual doses must be kept as low as reasonably achievable, taking economic and societal factors into account (ALARA principle). In order to be consistent with ALARA recommendations, shielding calculations use dose constraints instead of dose limits. These dose constraints are established by every national regulatory authority following the mentioned ICRP recommendations. Consequently, in order to verify the completion with regulatory standards, the annual effective dose results are compared with the dose constraints required by the corresponding national authority.

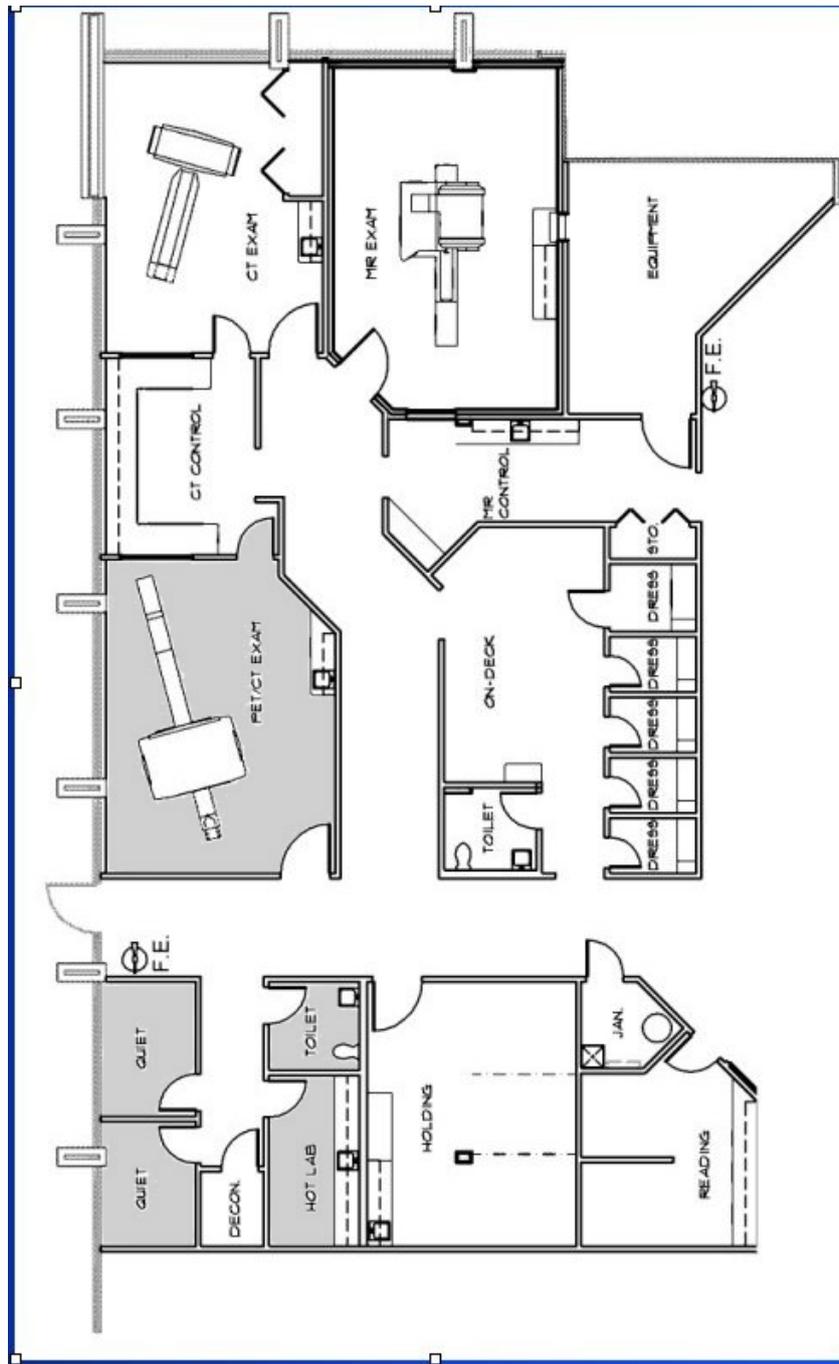


Figure 9. Room layout of a typical PET facility in a nuclear medicine clinic.

2.1 Parameters

Now, the parameters used in the evaluation procedure are discussed.

2.1.1 Effective dose rate constant, Γ

In radiation protection, the quantity of interest in shielding evaluation is effective dose; this quantity depends on incident photon energy and irradiation geometry. Figure 10 shows irradiation geometries encountered in common scenarios of radiation protection, and Figure 11 shows the effective dose dependence on specific irradiation geometries^[6]. During a given practice, it is usual to

have more than single irradiation geometry, consequently, in order to obtain the total effective dose one should use a combination of the mentioned geometries. Given an incident radiation, it is apparent from Figure 10 that antero-posterior irradiation geometry (A-P) yields the highest effective doses. Consequently, conservative assessment given by A-P geometry is used in shielding evaluation. Table 2 gives the corresponding values for this geometry.

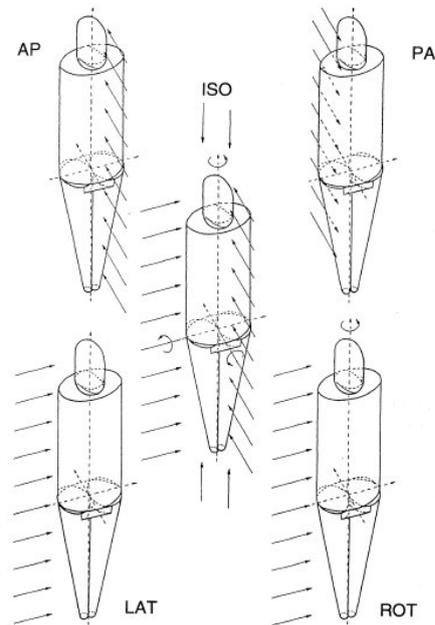


Figure 10. A Diagrammatic Representation of the Five Standard Irradiation Geometries selected by the ICRP and ICRU for the calculation of Conversion Coefficients in ICRU Report 57 (from ICRP Publication 74 and ICRU Report^{[6][7]})

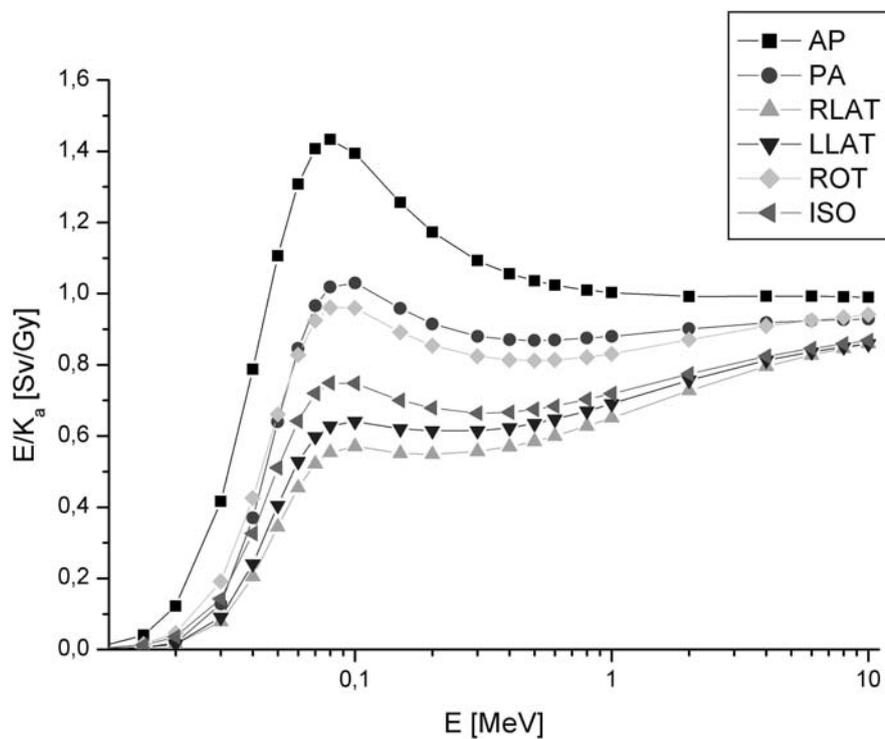


Figure 11. Effective dose per unit air kerma vs photon energy^[6]

Table 2: Photon effective dose conversion factor ^[6] in A-P geometry.

[MeV]	K_a/ϕ [pGy cm ²]	E/K_a [Sv/Gy]	E/ϕ [pSv cm ²]
0.010	7.43	0.00653	0.049
0.015	3.12	0.0402	0.125
0.020	1.68	0.122	0.205
0.030	0.721	0.416	0.300
0.040	0.429	0.788	0.338
0.050	0.323	1.106	0.357
0.060	0.289	1.308	0.378
0.070	0.298	1.407	0.419
0.080	0.307	1.433	0.440
0.100	0.371	1.394	0.517
0.150	0.599	1.256	0.752
0.200	0.856	1.173	1.00
0.300	1.38	1.093	1.51
0.400	1.89	1.056	2.00
0.500	2.38	1.036	2.47
0.600	2.84	1.024	2.91
0.800	3.69	1.010	3.73
1.000	4.47	1.003	4.48
1.500	6.14	0.998	6.12
2.000	7.55	0.992	7.49
3.000	9.96	0.993	9.89
4.000	12.1	0.993	12.0
5.000	14.1	0.993	14.0
6.000	16.1	0.993	16.0
8.000	20.1	0.991	19.9
10.000	24.0	0.990	23.8

Following these concepts, the effective dose rate constant of an unshielded point source is defined as the effective dose per unit time and per unit activity at 1m from the source. As stated before, in shielding evaluation antero-posterior geometry values are used. The effective dose rate constant for the radionuclides used in PET studies are calculated according to the conversion factors provided by ICRP Publication 74^[6] (see Table 2), using data from Table 1. The resulting constants may be seen in Table 3.

Table 3: Positron emitters radionuclides used in PET studies.
Half life ($T_{1/2}$), emissivity (ϵ), and effective dose rate constant (Γ).

Radionuclide	$T_{1/2}$	Photon energy [MeV]	ϵ	Γ [mSv m ² /h.MBq]
¹¹ C	20.4 min	0.511	2.00	1.44E-04
¹³ N	10.0 min	0.511	2.00	1.44E-04
¹⁵ O	2.0 min	0.511	2.00	1.44E-04
¹⁸ F	109.8 min	0.511	1.93	1.39E-04
⁶⁴ Cu	12.7 h	0.511 / 1.346	0.38 / 0.005	2.70E-05
⁶⁸ Ga	68.3 min	0.511	1.84	1.33E-04
⁸² Rb	76 s	0.511 / 0.776	1.90 / 0.13	1.50E-04
¹²⁴ I	4.2 d	0.511 / 0.603 / 1.693	0.5 / 0.62 / 0.3	1.45E-04

2.1.2 Administered Activity, A_0 / Uptake time, t_{up} / Acquisition time, t_{ac}

The amount of activity administered to a given patient depends on several factors such as mass of the patient, image acquisition mode, the length of the uptake time, PET tomograph, and so on. Generally adults receive 370-740 MBq (10-20 mCi) of ^{18}F while children receive 4-5 MBq / kg. As said above, after the injection patients lie down in the uptake room for about 45-60 minutes (uptake time) while the radionuclide distributes throughout their body. It is important for patients to be kept in a quiet resting state in order to reduce uptake in the skeletal muscles^[3]. After this, patients void their bladder of urine accumulation. Consequently, at the moment of the image acquisition the activity on the patient is

$$A(t_{up}) = A_0 \cdot e^{-\lambda \cdot t_{up}} - \alpha \cdot A_0 \quad (1)$$

where, $A(t_{up})$ is the remaining activity in the patient at the uptake time t_{up} , λ is the decay constant, A_0 is the administered activity and α is the fraction of the administered activity excreted by the patient before the acquisition of the images (typically $\alpha = 0.15-0.20$).

The information of the three mentioned parameters (the administered activity, the uptake time and the acquisition time) should be provided by the facility in the working procedure.

2.1.3 Transmission factor, k

The effective dose rate constant gives the dose rate produced by a given point source, with no shielding between the source and the point of interest. To take into account the effect of the shieldings interposed between any source and the point of calculation, a coefficient named transmission factor is used. The transmission factor is defined as

$$k = \frac{D(r_o)}{D_o(r_o)} \quad (2)$$

where, $D(r_o)$ is the dose at the interest point considering the shielding and $D_o(r_o)$ is the dose in the same point without considering the shielding. This factor may be defined for any source geometry, e.g. point or broad beam.

Since the body absorbs some of the annihilation radiation, the dose rate from the patient is reduced by a significant factor. Thus, in the evaluation of a PET facility, the building shieldings are considered as well as the patient attenuation (self-attenuation). Typical materials used as shielding in a PET facility are lead, iron, concrete, and masonry (common brick). The transmission factors applied were calculated by the Monte Carlo method^[3] considering broad beam geometry. In the original document, i.e. AAPM Task Group 108 : PET and PET/CT Shielding Requirements, transmission factors are given up to 50 mm for lead, 50 cm for concrete and 18 cm for iron. In this work, this range was extended by calculating the corresponding values with MCNPX Monte Carlo code^[8]. Table 4 shows the complete set of transmission factors for lead, concrete and iron, corresponding to the 511 KeV radiation. Figure 12 shows the plotting of the same transmission factors.

Table 4: Transmission factors for 511 KeV photon radiation

Thickness ^a	Lead	Concrete ^b	Iron
0	1.0000	1.0000	1.0000
1	0.8912	0.9583	0.7484
2	0.7873	0.9088	0.5325
3	0.6905	0.8519	0.3614
4	0.6021	0.7889	0.2353
5	0.5227	0.7218	0.1479
6	0.4522	0.6528	0.0905
7	0.3903	0.5842	0.0542
8	0.3362	0.5180	0.0319
9	0.2892	0.4558	0.0186
10	0.2485	0.3987	0.0107
12	0.1831	0.3008	0.0035
14	0.1347	0.2243	0.0011
16	0.0990	0.1662	0.0004
18	0.0728	0.1227	0.0001
20	0.0535	0.0904	2.50 10 ⁻⁵
25	0.0247	0.0419	7.88 10 ⁻⁷
30	0.0114	0.0194	
40	0.0024	0.0042	
50	0.0005	0.0009	
60	1.11 10 ⁻⁴	1.93 10 ⁻⁴	
70	2.38 10 ⁻⁵	4.14 10 ⁻⁵	
75	1.10 10 ⁻⁵	1.91 10 ⁻⁵	

^a Thickness in mm for lead, and cm for concrete and iron.

^b Concrete is considered to have a density of 2.35 g/cm³.

The patient self-attenuation depends on the energy distribution of the radiation source inside the patient itself. Studies found in the literature^[9] indicate that the mean transmission factor of a typical patient is approximately $k_{pat} = 0.64$ for radionuclides used in PET with a characteristic energy of 511 keV. For masonry, the transmission factors of concrete, modified by the relationship between densities, are used^[10].

$$\frac{\delta_{brick}}{\delta_{concr}} = \frac{X_{concr}}{X_{brick}} \quad (3)$$

where δ_{brick} is the masonry density, δ_{concr} is the concrete density, X_{brick} is the masonry thickness and X_{concr} is the equivalent concrete thickness. For shielding calculation purposes, masonry may be considered as a mix of common brick and mortar.

In case of a multilayer shield, the total transmission factor is obtained as a product of the individual transmission factors (included transmission of the patient, k_{pat})

$$k_{tot} = \prod k_i \quad (4)$$

where, k_{tot} is the total transmission factor for the whole shielding, and the k_i 's are the transmission factors of the individual ones.

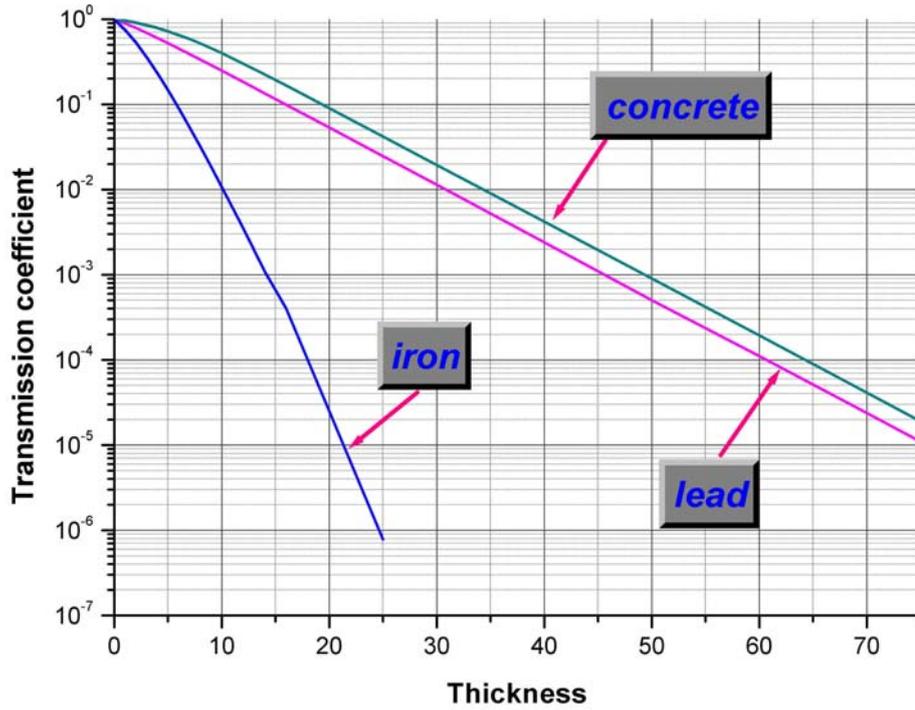


Figure 12. Transmission factors for 511 KeV photon radiation. Thickness in mm for lead, and cm for concrete and iron.

2.1.4 Dose reduction factor, R_t

As commonly radionuclides used in PET studies have short half-lives, it is necessary to consider their decay when the dose rate is integrated to yield the total dose. The result of the integration is

$$D(t) = \dot{D}_0 t \frac{1}{\lambda t} (1 - e^{-\lambda t}) \quad (5)$$

Looking at expression (5), we can define the so-called dose reduction factor as follows^[3]

$$R_t = \frac{D(t)}{\dot{D}_0 \cdot t} = \frac{1}{\lambda \cdot t} \cdot (1 - e^{-\lambda t}) \quad (6)$$

where, $D(t)$ is the effective dose accumulated during a time t , \dot{D}_0 is the initial effective dose rate and λ is the decay constant. In this way, the integrated dose is simply expressed as

$$D(t) = \dot{D}_0 \cdot t R_t \quad (7)$$

Table 5 shows dose reduction factor useful for typical situations encountered in PET diagnoses with ^{18}F . The value for 8 hours was supplied in order to represent a typical working day.

Table 5. Typical values for the dose reduction factor

t	R _t
30 min.	0.911
45 min	0.871
60 min.	0.832
90 min.	0.762
120 min	0.701
8 hours	0.314

2.1.5 Occupancy factor, T

The occupancy factor (T) for a given area or point of interest is defined as the average fraction of the effective irradiation time that a maximally exposed individual remains in the area or point of interest. It is important to stress that the occupancy factor for an area is not the fraction of time that it is occupied by any persons, but rather it is the fraction of time that it is occupied by the single person who spends the most time there. Thus, for example, a waiting room might be occupied at all the times during the working day, but have a very low occupancy factor since no single person is likely to spend more than 50 hours per year in a given waiting room. This value would imply an occupancy factor of $T = 50/2000 = 1/40$ for a normal working year. Instead, conservatively $T = 1/20$ is suggested by NCRP 151 (see Table 6). Occupancy factors in uncontrolled areas will rarely be determined by visitors to the facility or its surrounding areas, who might be there only for a small fraction of the year. The maximally exposed individual will normally be an employee of the facility^[10].

A value of unity is usually assigned to the occupancy factor for controlled areas. However, there can be situations in which access to a controlled area is restricted even for radiation workers when radiation is being produced (e.g., the control room). In such cases, the qualified expert designing the shielding requirements for that controlled area may use local information on occupancy of the area^[10].

In conclusion, the occupancy factor depends on both, the facility itself and the work procedure. In those cases where this information is not available, it is possible to apply the T values suggested in the bibliography^[10]. Table 6 shows these suggested values.

Table 6. Suggested occupancy factors (for use as a guide in planning shielding when other sources of occupancy data are not available)^[10].

Location	Occupancy Factor T
Full occupancy areas, administrative offices, treatment planning areas, treatment control rooms, nurse stations, attended waiting rooms, occupied space in nearby building	1
Adjacent treatment room, patient examination room adjacent to shielded vault.	1/2
Corridors, employee lounges, staff rest rooms.	1/5
Treatment vault door.	1/8
Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitors' closets.	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators.	1/40

2.2 Calculation model

As mentioned above, basically two types of radioactive sources are present in the facility: the patients themselves and the sources located in the hot lab. The sources in the hot lab are most of the time stored into a lead container, typically 5cm-thick. In Figure 13 can be found a typical lead housing into the hot lab with a raising device for manipulation of the shielded vial package. According to Table 4 the transmission factor in that case is $5 \cdot 10^{-4}$. As a consequence, doses due to these sources are usually negligible. In this work, only doses due to patients are considered; however it is recommended to do the dose assessment for each particular case.



Figure 13. Typical shielding for temporary storing of PET sources.

In all the calculations, a simplified model is used by considering point sources. This model is conservative enough to be used in radiation protection. As stated before, the quantity of interest in radiation protection is effective dose, which normally is expressed in annual form. Using formula 7 for the case of a point source, the annual effective dose at a point of interest, produced during a specific operation with that point source is given by

$$D = \Gamma \frac{A t_{op} N}{d^2} k R_t T \quad (8)$$

where, Γ is the effective dose rate constant of the source, A is the initial activity present into the patient at the beginning of the operation, t_{op} is the time length of the operation, N is the number of times that each operation is performed annually, d is the distance between the source and the point of interest, k is the total transmission factor taking into account all shields between the source and the point of interest (including the patient), R_t is the dose reduction factor and T is the occupancy factor at the point of interest. The only operations considered here are: 1) the patient at rest (uptake time) and 2) the patient in PET scanner (acquisition time). The total annual effective dose is calculated by adding the doses produced in both situations.

Because the 511 keV annihilation photons are so penetrating, it is necessary to consider controlled and uncontrolled areas above and below the PET facility as well as those adjacent on the same level. These also include all surrounding uncontrolled areas in the vicinity of the PET imaging clinic. Figure 14 shows generally accepted source and target distances that apply in these cases. Typically, one assumes that the patient (source of the activity) is 1 m above the floor. The dose rate is

calculated at 0.5 m above the floor for rooms above the source, and at 1.7 m above the floor for rooms below the source^[10].

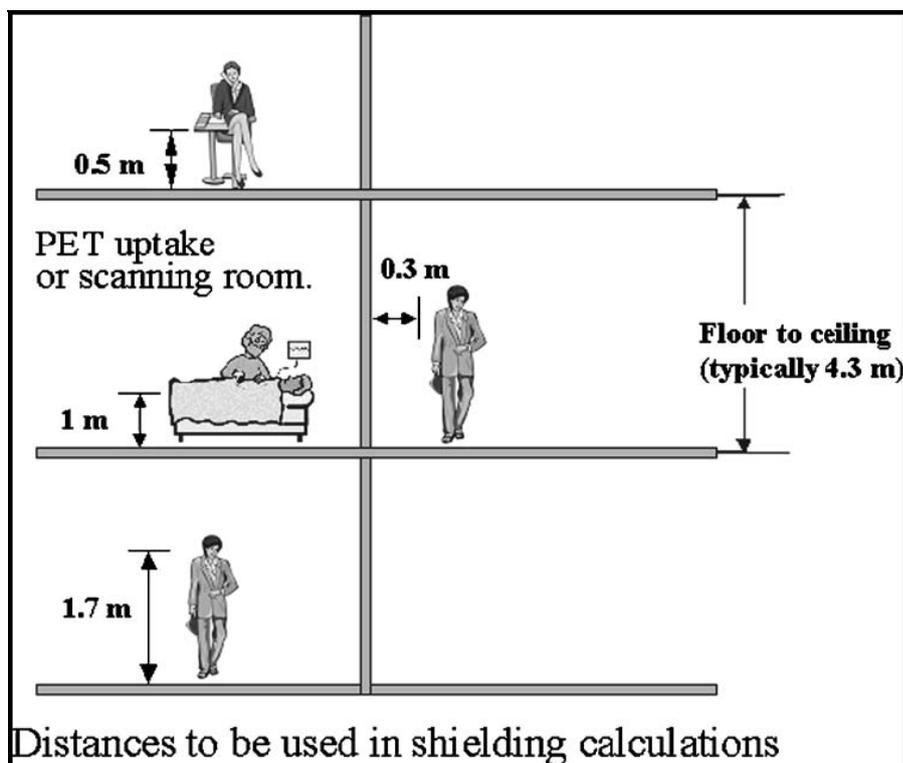


Figure 14. Generally accepted distances for PET calculations.

3. Evaluation guidelines and design considerations

In this section some evaluation guidelines are presented. Some simple cases are analysed applying the previous formulae, in order to draw conclusions about radiation protection. On the basis of the outcome a series of suggestions are made, which intend to provide a guide to improve both working procedures, and the facility design.

It has to be stressed that radiation safety must be guaranteed by the facility design itself and not by particular procedures. For example, if access to a given controlled area into the facility may not be restricted either by personnel or by any physical means, then shielding must be adequate for protection to the public, considering an occupancy factor of 1. This concept is of capital importance when considering surrounding uncontrolled areas in the vicinity of the PET facility. In this case, an occupancy factor of 1 must be used, because the facility itself cannot ensure the use given to that area: may be a garage nowadays, but a private building in the future. Instead, an uncontrolled area within the facility may be different because, in this case, it could be possible that facility can control the use given to that area.

Now, some guidelines for improving the shielding design of a typical PET facility will be presented. An average administered activity of 555 MBq (15 mCi) of ^{18}F , an uptake time of 60 min, and 40 patients per week will be supposed. For the sake of illustration, dose constraints required by the Nuclear Regulatory Authority of Argentina will be used: 5 mSv per year for occupational exposure, and 100 μSv per year for public exposure^[11].

In a complete PET study, a set of operations is performed (detailed in the working procedure of the clinic), and each operation is performed one time per each patient. In the typical clinic described

here 40 patients are attended per week, so that, the number of times each operation is repeated during one year would be equal to the number of patients per year, i.e.

$$N = 40 \frac{\text{pat}}{\text{week}} \times 52 \frac{\text{week}}{\text{year}} = 2080 \frac{\text{pat}}{\text{year}}$$

Prior to injection to patient, the needed radioactive aliquot has to be transferred from the vial to the syringe. This operation is carried out interposing a lead shield between the vial and the operator. The shield used in this case is the lead glass that is structural part of the top cover of the lead container (see Figure 13). This operation may be seen at Figure 15.



Figure 15. Transferring of the radioactive aliquot from the vial to the syringe.

Because of the high effective dose constant associated with positron-emitting radionuclides, hand doses for individuals drawing up and administering PET radiopharmaceuticals can be substantial. For example, the dose rate at 5 cm from an unshielded syringe with a typical administered activity is

$$\dot{D} = \frac{\Gamma A}{d^2} = \frac{1.39 \cdot 10^{-4} \text{ mSv m}^2 / \text{h MBq} \times 555 \text{ MBq}}{(0.05 \text{ m})^2} = 30.86 \text{ mSv/h}$$

that is, about 31 mSv/h. Assuming, conservatively, that each application takes 1 minute, the annual hand dose to a technician would be

$$D = 31 \frac{\text{mSv}}{\text{h}} \times \frac{1}{60} \frac{\text{h}}{\text{pat}} \times 2080 \frac{\text{pat}}{\text{year}} = 1070 \frac{\text{mSv}}{\text{year}} !!!$$

Tungsten syringe shields can reduce the hand dose, but the additional weight can make injections difficult. An example of a syringe shield may be seen at Figure 16.



Figure 16. Typical syringe shield used in PET studies.

On the other hand, after the syringe was loaded with the radioactive solution, it has to be translated through the facility up to the uptake room, where the patient is injected. In order to minimize dose to technicians (and to a lesser extent to members of the public), this translation is made with the syringe located within a cylindrical lead shielding (see Figure 17).



Figure 17. Cylindrical lead shielding for syringe translation.

The injection may be administered to the patient using a catheter, with the syringe located within the mentioned lead shielding (see Figure 18), but other ways to reduce hand dose are to use automatic dispensing systems and to divide the injection responsibilities among the staff.



Figure 18. Administration of an injection to the patient.

If a single member of the staff would remain at 1 m from the patient during uptake time, then the dose to this technician would be (according to formula (8))

$$k = 0.64 \quad (\text{patient attenuation})$$

$$t_{op} = 1 \text{ h} \Rightarrow R_t(1\text{h}) = 0.832 \quad (\text{dose reduction factor for one hour integration})$$

$$T = 1 \quad (\text{full occupation})$$

$$D = \frac{1.39 \cdot 10^{-4} \text{ mSv m}^2 / \text{h MBq} \times 555 \text{ MBq}}{(1 \text{ m})^2} \times 1 \text{ h} / \text{pat} \times 2080 \text{ pat} / \text{year} \times 0.64 \times 0.832 \times 1 = 85 \text{ mSv} / \text{year}$$

Consequently, the staff should develop procedures to minimize the time spent near the radioactive patient. Information collection, explanations, and blood collection or other tests should be performed as much as possible before radioactivity has been administered. Remote monitoring of the patients using video cameras can also be used to reduce the time technologists and nurses spend in close proximity to the patients. In other words, the practice should be optimized.

By applying formula (1), at the time the patient is being positioned for imaging, his initial activity is found to be

$$\begin{aligned} A(t_{up}) &= A_0 \cdot e^{-\lambda \cdot t_{up}} - \alpha \cdot A_0 = 555 \text{ MBq} \times \exp\left(-\frac{\ln 2}{109.8 \text{ min}} \times 60 \text{ min}\right) - 0.15 \times 555 \text{ MBq} \\ &= 297 \text{ MBq} \end{aligned}$$

The time for carrying the patient up to the acquisition suite and accommodate him in the correct position could be, conservatively, about 3 minutes, so that the dose to the technician from this operation would be

$$t_{op} = 3 \text{ min} \Rightarrow R_t(3 \text{ min}) \cong R_t(0) = 1$$

$$D = \frac{1.3910^{-4} \text{ mSv m}^2 / \text{h MBq} \times 297 \text{ MBq}}{(1 \text{ m})^2} \times \frac{3 \text{ h}}{60 \text{ pat}} \times 2080 \text{ pat/year} \times 0.64 \times 1 \times 1 = 2.75 \text{ mSv/year}$$

From the calculations carried out it is apparent that it is feasible for a single technician to exceed the dose constraint (5 mSv in the present case). The only reasonable way to lower this dose is to have enough staff so that the contact time between radioactive patients and any one staff member can be diluted.

The gantry and detectors of the PET tomograph can provide a substantial reduction of the dose rate at some of the walls. This depends on the actual geometry and placement of the tomograph in the room as well as the type of scanning procedures. If information on the tomograph shielding characteristics is available from the vendor, it can be incorporated into the calculation for the walls that are shielded by the scanner and for the floors and ceilings. Normally the most conservative approach is taken, i.e. no shielding from the tomograph is assumed. In this way, the calculation of shielding for the tomograph room is similar to the uptake area calculation. During the patient image acquisition, at least one technologist is located at the PET system console where both the patient and the progress of the imaging study can be monitored. Ideally, the console area should be located more than 2 m away from the scanner to reduce the operator dose below ALARA levels. Using formula (8) with these assumptions the dose to console operator from patient at PET scanner is found to be

$$D = \frac{1.3910^{-4} \text{ mSv m}^2 / \text{h MBq} \times 297 \text{ MBq}}{(2 \text{ m})^2} \times 1 \text{ h/pat} \times 2080 \text{ pat/year} \times 0.64 \times 0.832 \times 1 = 11.4 \text{ mSv/year}$$

In order to make a simple didactical calculation it can be assumed that patient at PET scanner is the only radioactive source. In this case, the transmission factor needed to comply with the 5 mSv/year dose constrain would be

$$k = \frac{5 \text{ mSv/year}}{11.42 \text{ mSv/year}} = 0.4378$$

which, according to table 4, corresponds to about 7 mm of lead ($k=0.3903$). Of course any combination of materials may be used to obtain the same value. For example if a layer of 2 mm of lead were used ($k=0.7873$), then the needed additional layer of concrete would be

$$k = 0.4378 = 0.7873 \times k_{conc} \Rightarrow k_{conc} = 0.5561$$

which corresponds to about 8 cm of concrete ($k=0.5180$). In other case, if masonry of mean density $\delta = 1.6 \text{ g/cm}^3$ is used, the equivalent thickness would be (see formula (3))

$$X_{brick} = \frac{2.35 \text{ g/cm}^3}{1.60 \text{ g/cm}^3} \times 8 \text{ cm} \cong 12 \text{ cm}$$

New facilities can efficiently use concrete to achieve required shielding factors, while in existing facilities, lead is often the best resort. Portable lead shields can be used effectively to shield patients in uptake rooms where they are required to remain stationary. Planning for new PET facilities should carefully consider the constraints associated with the regulatory limits. Uncontrolled areas with high occupancy should be located as far as possible from the uptake and imaging rooms. Also, the placement of the door must be carefully considered to avoid the expense with installing one with

substantial lead shielding. If uncontrolled areas are located above and below the PET uptake and tomograph rooms, the spacing between floors may need to be greater than normal. If that is not feasible, the floors need to be able support the weight associated with additional shielding. Floors often (but not always) have 10 cm of concrete, which will provide a dose reduction factor of 2.5. It is a good idea to have the hot bathroom, reserved for PET patients, within the immediate imaging area so that they do not alter the background counts of other detection devices as they pass through the clinic. The patient may be released immediately following the procedure or may go to a waiting area while the PET study is reviewed. If the patients are kept in the clinic for any length of time after the study is completed, that area must also be included in the radiation safety planning.

It should be noted that the lead shielding required in the walls for the CT system alone (i.e. ignoring the PET component) will have only a modest shielding effect for the 511 keV annihilation radiation. For example, 1.6 mm of lead will provide a transmission factor of only 0.81 for the annihilation radiation. Because the half value layer (HVL) for the CT x rays is so much smaller than that for 511 keV photons, a room that is shielded to meet the general public levels for PET usually is unlikely to need additional shielding for the CT component.

References

1. <http://www.pethistory.us/>
2. <http://www.cerebromente.org.br/>
3. Mark T. Madsen et al, "AAPM Task Group 108 : PET and PET/CT Shielding Requirements", Med. Phys, 33(1), 2006. INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION.
4. PET/CT SHIELDING DESIGN COMPARISONS A Thesis by Audra Lee Coker. Submitted to the Office of Graduate Studies of Texas A&M University in partial fulfilment of the requirements for the degree of Master of Science May 2007. Available in <http://repository.tamu.edu/bitstream/handle/1969.1/5836/etd-tamu-2007A-HLPH-Coker.pdf?sequence=1>
5. Annals of the ICRP PUBLICATION 103: The 2007 Recommendations of the International Commission on Radiological Protection, Editor J. Valentin
6. Conversion Coefficients for Use in Radiological Protection against External Radiation. ICRP Publication 74 (1997).
7. International Commission on Radiation Units and Measurements. *Conversion Coefficients for use in Radiological Protection against External Radiation*. ICRU Report 57. Bethesda, Maryland; ICRU (1998).
8. Los Alamos National Laboratory): TPO-E83-G-UG-X-00001, November 14,1999. MCNPX™ User's manual, Version 2.1.5, Laurie S. Waters, Editor. LA-CP-05-0369 MCNPXTM USER'S MANUAL Version 2.5.0, April 2005, Denise B. Pelowitz, editor
LA-UR-08-1808, MCNPX 26F Extensions, MARCH 24, 2008
9. Benjamin W. Zeff et al, "Patient self-attenuation and technologist dose in positron emission tomography", Med.Phys. 32(4), 2005.
10. NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS. Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities. NCRP Report N° 151 (2005).
11. Norma Básica de Seguridad Radiológica, AR 10.1.1 Revisión 3. <http://www.arn.gov.ar/normas/10-1-1R3.pdf> (only available in Spanish).

Bibliography

- PET/CT basics with quality pictures may be seen at <http://www.med-ed.virginia.edu/courses/rad/PETCT/index.html>

- Wahl RL, Buchanan JW (editors): Principles and Practice of Positron Emission Tomography. Philadelphia, Lippincott, Williams, & Wilkins, 2002.
- J. C. Courtney *et al.*, “Photon shielding for a positron emission tomography suite,” Health Phys. 81, S24–28 (2001).
- Radiation oncology physics: a handbook for teachers and students / editor E. B. Podgorsak ; sponsored by IAEA Vienna : International Atomic Energy Agency, 2005.