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Shielding Calculation for Nuclear Medicine Services

Cálculo de Blindajes Para Servicios de Medicina Nuclear

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Abstract

Nuclear medicine is a medical specialization that uses radioactive materials injected into the body to diagnose and treat human diseases. The use of different radionuclides and high amounts of radioactive materials makes it necessary for the facilities where these procedures are conducted to evaluate the corresponding shielding to comply with the design dose limits of a facility and avoid radiological accidents as recommended and accepted in international publications, like the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP). This work compares two methods to calculate the shielding necessary to guarantee que las medicine service zones be safe from ionizing radiations. The first method consists in calculating the transmission factor B to find the thickness of the material necessary to protect the zone of interest, this factor is calculated by bearing in mind the occupancy factors, workloads, use factor, and the design objective dose limit. Upon obtaining the transmission factor B, half value layer (HVL) or tenth value layer (TVL) tables are used for each construction material, obtaining the thickness of the material. The other method is the calculation of is the calculation of rates of exposure through the air Kerma rate constant, then the XCOM databases are used, which were developed by the National Institute of Standards and Technology (NITS) to obtain the attenuation coefficient, used in the law of exponential attenuation; finally, the necessary thickness of the material is obtained to reach the design objective. Finally, the principal differences between both methods are shown and an analysis is performed of the shielding optimization, seeking to set criteria to make recommendations to nuclear medicine services on optimal shielding..

Keywords: Dose rate limits, Radionuclides, Shielding, Transmission Factor B, Attenuation Coefficient, Use Factor, Occupancy Factor, Workload, Air Kerma Rate Constant, XCOM.

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Resumen

La medicina nuclear es una especialidad médica que utiliza materiales radioactivos inyectados en el cuerpo para diagnóstico y tratamiento de enfermedades humanas. El uso de diferentes radionúclidos y altas cantidades de materiales radiactivos hace necesario que las instalaciones donde se realicen estos procedimientos evalúen los blindajes correspondientes para cumplir los límites de dosis de diseño de una instalación evitando así accidentes radiológicos recomendados y aceptados en las publicaciones internacionales como el ICRP (International Commision on Radiological Protection) y el NCRP (National Council on Radiation Protection and Measurments). En este trabajo se comparan dos métodos para el cálculo de los blindajes necesarios para garantizar que las zonas del servicio de medicina sean seguras a las radiaciones ionizantes. El primer método consiste en calcular el factor de transmisión B para hallar el espesor del material necesario para proteger la zona de interés, este factor se calcula teniendo en cuenta los factores de ocupación, cargas de trabajo, factor de uso y el límite de dosis objetivo de diseño. Una vez obtenido el factor de transmisión B se usan las tablas de HVL (Half Value Layer) o TVL (Tenth Value Layer) para cada material de construcción obteniéndose el espesor del material. El otro método es el cálculo de las tasas de exposición por medio de la constante de la tasa de Kerma en Aire, luego se usan las bases de datos (XCOM) desarrolladas por NITS (National Institute of Standards and Technology) para obtener el coeficiente de atenuación que son utilizados en la ley exponencial de atenuación; finalmente, se obtiene el espesor de material necesario para alcanzar el objetivo de diseño. Finalmente, se muestran las principales diferencias entre los dos métodos y se hace un análisis de la optimización de los blindajes buscando tener criterios para hacer recomendaciones a los servicios de medicina nuclear sobre blindajes óptimos.

***Palabras clave*:** Límites de Tasa de Dosis, Radionúclidos, Blindaje, Factor de Transmisión B, Coeficiente de Atenuación, Factor de Uso, Factor de Ocupancia, Carga de Trabajo, Constante de la Tasa de Aire en Kerma, XCOM.

1. Introduction

Nuclear medicine is a branch of medicine which diagnoses through images and treatments by using ionizing radiations emitted by radionuclides [2] [3] [4], like 99mTc [5] [6], 131I [7], 177Lu [8], 188Re, 90Y, 67Ga, 123In, 32P, among others. During the design of the facility to comply with regulatory norms [9] in radiation protection, it is necessary to provide the shielding study, besides assuming all the security requirements [10], like demarcation of controlled and uncontrolled zones [11], limits and restrictions for the dose rate [12] [14]. These must comply: 1. For workers exposed, the dose rate must be below 20 mSv/year=0.4 mSv/week=10 μSv/h and 2. For the public in general, the dose rate must be 1 mSv/year=0.02 mSv/week=0.5 μSv/h. The International Atomic Energy Agency (IAEA) recommends within the considerations not using directly the permitted dose limit, but the following restrictions for the annual dose: 1. for controlled zones, do not exceed a dose rate of 5 mSv/year and 2. for uncontrolled zones, do not exceed 0.3 mSv/year [12] [13] [14], this restriction is denoted with $\dot{D}$.

From the implications of supposing work with point sources with a possible maximum activity according to the service [15], used for each radionuclide, the workload will be determined denoted with the variable W in equation (1), which represents an estimation of the dose [16] per week of each radionuclide used by the facility. This parameter depends on the physical characteristics of said radionuclides, which is reflected on the direct dependency on the air Kerma rate constant (Γδ) [17]. In turn, the workload will depend on the number of patients per week, N, who receive a specific radionuclide and the average time of permanence of said radionuclide in a given specific place. To determine the air Kerma rate, the methodology exposed in [18]–[20] is used, which determines said physical parameter from the gamma ray specific constant; this is for energy above 20 KeV, given that it is considered that smaller energies are absorbed in a syringe or vial [21], thus, constituting insignificant danger for patients, public, and occupational staff. The units worked are (μGy m^2)/(h GBq). The following conversion is used:

$$1\,\frac{\text{R m}^2}{\text{h Ci}} = 236.1\,\frac{\mu\text{Gy m}^2}{\text{h GBq}}$$

Table 1 shows some characteristics of the radionuclides used most in nuclear medicine, where $T_{1/2}$ is the mean life time of the radioisotope, defined as the time elapsing until the amount of radioactive nuclei of a radioactive isotope is reduced to half the initial amount. N is the number of patients (or number of preparations of radionuclides) weekly; the data were obtained from considerations in reference [22].

2. Generalities: Shielding Calculation

The workload, W, of each radionuclide is the principal characteristic to conduct the shielding study, given that it indicates an approximation of the amount of radiation present in a given area of the facility during a specific time interval; it is determined through equation (1):

$$W = \Gamma_{\delta} * A * N * t \left[\frac{\mu\text{Gy m}^2}{\text{week}}\right] \tag{1}$$

Where A is the maximum activity in $\left[\frac{\text{GBq}}{\text{Patient}}\right]$, t defines the permanence time of the radionuclide in a given place of the facility in hours.

2.1. Calculation: Dose rate

The equivalent dose rate $\left(\dot{D}_0\right)$ [27] produced by a radionuclide [28] is calculated from equation (2):

$$\dot{D}_0 = \frac{W*U*T}{d^2}\left[\frac{\mu\text{Sv}}{\text{week}}\right] \tag{2}$$

Here T is the occupancy factor, U is the use factor [29], and d is the distance from the specific source (radionuclide) to the point of interest under study.

Equation (2) shows that W is given in µGee m^2/week units, and the equivalent dose rate in µSv/week units; the change from units of dose to equivalent dose is due to the weighting factor of the type of radiation, which for the photon rays is equal to 1 and permits changing from Gy to Sv.

Equation (2) can also be written and corrected by other factors that permit more specific approximation to radiation in nuclear medicine.

3. Correction Factor

3.1.1. Use factor

This is a fraction of the workload for which the point source of the radionuclide (or a radiation beam) is aimed at the place to be protected. Use factors can be classified in the following manner: Floor and ceiling: U = 1 and Walls: U= ¼, when the beam is due to a natural source, use factor is 1 in any direction

3.1.2 Occupancy factor

It is the factor by which we must multiply the workload to bear in mind the degree of occupation related to the zones considered for protection, the zones are classified into:

Table 1 Physical characteristics of radionuclides most used in nuclear medicine, in center of reference [19] [22] [23] [24] [25] [26].

Radio-nuclide	$T_{1/2}$ [h]	Energy [KeV]	Γδ $\left[\frac{\text{uGy m}^2}{\text{GBq h}}\right]$	N $\left[\frac{\text{Patients}}{\text{week}}\right]$
99m Tc	6.02	140.470	13.9299	70 cardiac analysis (rest and stress). 25 bone scan.
131 I	192.96	80.180	50.9503	4
177 Lu	161.04	71.650	3.7776	1
90 Y	3.19	202.510	83.0363	1
67 Ga	78.26	91.266	18.6046	1
123 In	1.66E-3	174.180	122.2761	1

Total occupation: T = 1. Work areas, laboratories, offices, workshops, shops, counselling offices, reception areas, and wide hallways that permit placing tables or showcases, dark rooms, homes, children's zones, etc.

Partial occupation: T = 1/5. Narrow hallways, waiting roo ms, baths, and elevators with operators

Occasional occupation: T = 1/40. Exterior parts, cleaning rooms, stairs, automatic elevators, parking lots, etc.

3.1.3. Decay factor of the radioisotope

The radioisotope decay factor refers to the disintegration of the radionuclide over time; it is defined with equation (3)

$$R(t) = \frac{1.44T_{\frac{1}{2}}}{t}\left(1 - e^{-\frac{t\ln(2)}{T_{\frac{1}{2}}}}\right) \tag{3}$$

To incorporate the radioactive material into the patient, we must calculate a decay factor through Ru incorporation during the time of incorporating the Tu material [31].

Also, when scanning the image from the gamma chamber [32], [33], we speak of a decay factor through taking an image denoted as Ri, which requires t_i image taking time.

3.1.4. Decay factor after incorporating the radiopharmaceutical.

When the radionuclide or radiopharmaceutical is incorporated, the disintegration manner changes because it can be excreted from the body through different mechanisms, with the radionuclide acting not only on the physical decay, but also on the biological decay [34]. Both the physical and biological decay constitute the effective mean life time $T_{1/2\text{eff}}$ [35] [36], defined by equation (4).

$$\frac{1}{T1/2_{Eff}} = \frac{1}{T1/2_{Phy}} + \frac{1}{T1/2_{Bio}} \tag{4}$$

Here $T_{1/2\text{Phy}}$ is the mean physical lifetime and $T_{1/2\text{Bio}}$ is the mean biological life time. Generally, the biological mean lifetime is difficult to identify precisely, given that each individual has different metabolic activities and, hence, the amount of radionuclide expelled through sweat, urine, and fecal matter changes from one patient to another. However, biological mean life tables exist, thus, the decay factor, after incorporating the radiopharmaceutical F, is defined in equation (5):

$$F = e^{-\ln(2)\left(\frac{t_u}{T1/2_{Eff}}\right)} \tag{5}$$

Here t_u is the patient's permanence time in an area with the radiopharmaceutical incorporated. This time can range between 30 min and 3 h. This factor represents the reduced activity of the source during absorption of the radionuclide by the patient's organism. The effective time for T_{c99m} is 4.8 h.

Considering the correction factors exposed, equation (2) takes the general form:

$$\dot{D}_0 = \frac{W*T*U*R*F}{d^2}\left[\frac{\mu\text{Sv}}{\text{week}}\right] \tag{6}$$

If seeking to determine the calculation of the radionuclide dose from an incorporation room, whose incorporation time is (tu), the annual dose rate will be:

$$\dot{D}_0(tu) = \frac{W*T*U*R_{tu}}{d^2} * 52\left[\frac{\mu\text{Sv}}{\text{year}}\right] \tag{6.a}$$

If seeking to determine the calculation of dose at a given distance, from the image or scan room whose image time is (ti), the dose rate is:

$$\dot{D}_0(ti) = \frac{W*T*U*R_{ti}*F_{tu}}{d^2} * 52\left[\frac{\mu\text{Sv}}{\text{year}}\right] \tag{6.b}$$

4. Calculation methods

Protection against ionizing radiations [37] seeks to reduce the doses that can eventually be received by occupationally exposed personnel (OEP) and the public, keeping said doses below pre-established values, based on recommendations from the International Atomic Energy Association (IAEA) and the International Commission for Radiation Protection (ICRP) [1] [10] [24] [38]. In general, the magnitude and probability of exposure by the OEP and the public will be restricted to the lowest levels that can be reasonably reached.

4.1 Method: Transmission factor

Transmission factor B [29] is defined as the ratio between the annual dose rate at a given distance with shielding system (seeking for the annual dose to agree with the international restriction that depends on the definition of the type of adjoining zone, whether controlled or not controlled) and the annual dose rate in the same point without shielding. From the definition, and using equation (6), we obtain:

$$B = \frac{\dot{D}}{\dot{D}_0} = \frac{d^2}{W*U*T*F*R*52}\dot{D} \tag{7}$$

The transmission factor for a radioactive material incorporation room is:

$$B = \frac{\dot{D}}{\dot{D}_0} = \frac{d^2}{W*U*T*R*52}\dot{D} \tag{7.a}$$

The transmission factor for an imaging ward is:

$$B = \frac{\dot{D}}{\dot{D}_0} = \frac{d^2}{W*U*T*F*R*52}\dot{D} \tag{7.b}$$

Barrier thickness is obtained from the expression:

$$\dot{D} = \dot{D}_0 e^{-\mu x} \tag{8}$$

Here μ is the attenuation coefficient, upon relating equations (7) and (8). B can be written as:

$$B = e^{-\mu x} \tag{9}$$

To reduce the dose rate by half, the half value layer (HVL) is used [39] and to reduce it to the tenth part, the tenth value layer (TVL) was used.

Tables exist to register HVL and TVL values, whose thicknesses depend on the type of material to shield [40] [41], the type of radionuclide that needs to be attenuated, and the energy from gamma rays it emits [12] [42] [43] [44] [45]

From equations (8) and (9), we have:

$$\mu = \frac{\ln(2)}{HVL} \tag{10}$$

And,

$$x = -(\log_2 B) * HVL \tag{11}$$

Using TVL:

$$\mu = \frac{\ln(10)}{TVL} \tag{12}$$

And,

$$x = -(\log_{10} B) * TVL \tag{13}$$

Equation (13) can be written in function of nHVL-times HVL or nTVL-times TVL, with n_{HVL} = $\log_2$ (1/B) and n_{TVL}=$\log_{10}$ (1/B), respectively.

4.2 Method: Attenuation factor

This method uses the materials proposed for construction, suggested in the NCRP 151 [12] and 147 [46] publications, with the most distinguished being ordinary concrete and lead, with densities ρ of 2.3 g cm^{-3} and 11.4 g cm^{-3} respectively [44] [47].

From equation (8), we have:

$$x = -\frac{1}{\mu}\ln\left(\frac{\dot{D}}{\dot{D}_0}\right) \tag{14}$$

The μ factor is obtained from the energy registered for the study in the XCOM database [44], which exists for concrete and lead, where mass transmission coefficient is obtained and, hence, the attenuation factor.

5. Results

According to Table 1, we noted that the radioisotope with the greatest workload associated to the big difference of use between the radionuclides related is the Tcm99; hence, the shielding determined for this radioisotope will meet the facility's need for radiation protection.

The procedures used with the Tcm99 are cardiac studies, which require two moments for image acquisition (at rest and under stress), and the bone scans.

For cardiac studies [48], [49], the procedure is:

1. In the radioactive material incorporation room, the patient is injected with Tcm99; this takes approximately 0.033 h
2. The patient rests during 1.5 h in the radioactive material incorporation room.
3. The patient goes to the Gamma chamber for imaging during 0.5 h.
4. Again, the patient returns to the radioactive material incorporation room for a new Tcm99 injection, this lasts 0.033 h.
5. The patient rests again for 1.5 h in the incorporation room.
6. After resting, the patient, in the same ward performs cardiac activities during 0.25 h (exercise-stress).
7. The patient is again taken to the Gamma chamber for a new image with a duration of 0.5 h.

Thereby, a patient lasts approximately 3.316 h in the radioactive material rest and incorporation ward and 1 h in the gamma chamber, for a procedure total of 4.316 h.

For osseous studies [50]:

1. In the radioactive material incorporation room the patient is injected Tcm99, this lasts approximately 0.033 h.
2. The patient rests during 1.5 h in the radioactive material incorporation room.
3. The patient is taken to the Gamma chamber for imaging during 0.5 h.

Thereby, a patient lasts approximately 1.533 h in the radioactive material incorporation room and 0.5 h in the gamma chamber.

Table 2 Workload of the Tcm99 radionuclide used most in nuclear medicine.

Radionuclide	Maximum Activity (GBq)	W (uGy m^2/week)
99m Tc	1.47 Gamma chamber	1433.38 (cardiac) + 91.94 (osseous)
99m Tc	1.47 Rest room	524.76 (cardiac) + 271.91 (osseous)

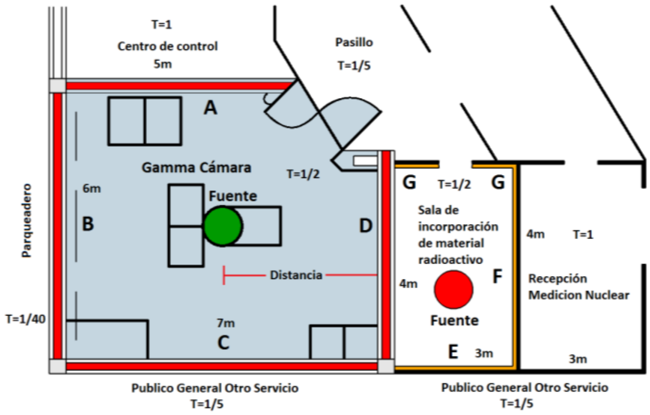

Figure 1 Structural plan, gamma chamber ward.

According to equation (1), we can find the workload presented by both specific sites where the radioactive material is manipulated (Gamma chamber and incorporation-rest room); this is determined in Table 2. The workload due to the use of Tcm99 will be the sum of the loads produced by the cardiac and osseous studies in each of the areas where it is manipulated.

In the shielding calculation, it is important to have an architectural floor plan of the nuclear medicine service to limit the controlled and uncontrolled zones and place the specific loads, distances, barriers, and occupancy factor, as shown in Fig.1.

Table 3 Workloads for use of Tcm99 in the Gamma chamber and radioactive material incorporation room.

Gamma chamber – Cardiac procedure without stress.		
Walls	Permanence time (h)	W ($uGy*m^2/week$)
A,B,C,D	0.5	716.69
Gamma chamber – Cardiac procedure with stress.		
Walls	Permanence time (h)	W ($uGy*m^2/week$)
A,B,C,D	0.5	716.69
Gamma chamber – Osseous procedure.		
Walls	Permanence time (h)	W ($uGy*m^2/week$)
A,B,C,D	0.5	91.94

Incorporation room – Cardiac procedure without stress.		
Walls	Permanence time (h)	W ($uGy*m^2/week$)
D,E,F,G	0.36	516.02
Incorporation room – Cardiac procedure with stress.		
Walls	Permanence time (h)	W ($uGy*m^2/week$)
D,E,F,G	0.61	874.37
Incorporation room – Osseous procedure.		
Walls	Permanence time (h)	W ($uGy*m^2/week$)
D,E,F,G	0.98	271.91

Figure 1 shows that both locations with the possible exposure sources are the Gamma chamber and the incorporation-rest room, in addition to identifying the adjoining areas with each of them. The Gamma chamber adjoins wall A with the command room, wall B with the parking lot, wall C with the ward for the general public, and wall D with the incorporation room.

Table 4 Annual dose rate.

Gamma chamber – Cardiac procedure without stress.				
Wall	Use F.	Occupancy F.	Distance (m)	Annual dose (uSv)
A	1	1	3	3225.03
B	1	0.03	3	96.75
C	1	0.20	2.5	928.81
D	1	0.5	3.5	1184.71
Gamma chamber – Cardiac procedure with stress.				
Wall	Use F.	Occupancy F.	Distance (m)	Annual dose (uSv)
A	1	1	3	3112.05
B	1	0.03	3	93.36
C	1	0.20	2.5	896.27
D	1	0.5	3.5	1143.20
Gamma chamber – Osseous procedure.				
Wall	Use F.	Occupancy F.	Distance (m)	Annual dose (uSv)
A	1	1	3	417.92
B	1	0.03	3	12.54
C	1	0.20	2.5	120.36
D	1	0.5	3.5	153.52
Incorporation room – cardiac exam without stress				
Wall	Use F.	Occupancy F.	Distance (m)	Annual dose (uSv)
D	1	0.5	1.5	5841.02
E	1	0.2	1.7	1819.00
F	1	1	1.5	11682.03
G	1	0.2	2.5	841.11
Incorporation room – cardiac exam with stress				
Wall	Use F.	Occupancy F.	Distance (m)	Annual dose (uSv)
D	1	0.5	1.5	9757.19
E	1	0.2	1.7	3038.57
F	1	1	1.5	19514.37
G	1	0.2	2.5	1405.03
Incorporation room – osseous test				
Wall	Use F.	Occupancy F.	Distance (m)	Annual dose (uSv)
D	1	0.5	1.5	2972.00
E	1	0.2	1.7	925.54
F	1	1	1.5	5944.01
G	1	0.2	2.5	427.97

The incorporation room is next to wall D Gamma chamber, wall E with the ward for the general public, F with nuclear medicine reception, and G with the hallway.

Table 3 specifies the workload in each of the areas of interest. For calculation, the maximum possible activity of 1.47 GBq per patient was used, along with the factor of air Kerma rate constant for the Tcm99 from Table 1.

To calculate the annual dose rate (Table 4), expressions (6.A) and (6.B) are used for the incorporation room and Gamma chamber, respectively. The decay factors in the Gamma chamber for cardiac exam (without stress and under stress) use image time of 0.5 h, obtaining a factor of 0.97, while the osseous test uses a test time of 0.33 h for a factor of 0.98. The incorporation factors in the Gamma chamber for cardiac exam without stress, under stress, and osseous exam are 0.80, 0.77, and 0.80, respectively.

These correspond to incorporation times of 1.53, 1.78, and 1.53 h, respectively. The effective time for Tcm99 is 4.8 h. Duration times in the incorporation room during a cardiac exam without stress, under stress, and osseous exam are 0.36, 0.61, and 0.98, respectively, to obtain decay factors of 0.98, 0.97, and 0.95, respectively.

The total accumulated dose through Tcm99, in each zone of interest, is the sum of the dose contributions of each type of study conducted; this is evidenced in Table 5.

Table 5 Total annual dose of Tcm99, in each zone of interest.

Contribution of Tcm99 in Gamma chamber	
Wall	Total annual dose (mSv/year)
A	6.76
B	0.20
C	1.95
D	2.48
Contribution of Tcm99 in Incorporation room	
Wall	Total annual dose (mSv/year)
D	18.57
E	5.78
F	37.14
G	2.67

5.1 Calculation through transmission factor B

The transmission factor is obtained from the total doses found in Table 5 and the dose restriction shown of 5mSv/year for workers exposed and 0.3mSv/year for the public. Transmission factors are observed in Table 6.

To determine the shielding thickness required in each of the sites of interest, equation (13) was used, which requires TVL for Technetium [42], [45] ($TVL_{Concrete}$= 6.6 cm and TVL_{Lead} = 0.83 mm); results are shown in Table 7.

If we consider a more conservative value for the occupancy factor equal to 1 in all the areas of interest, the results are shown in Table 8.

5.2 Calculation through attenuation factor

From equation (15), using specific mass coefficient for energy of Tc-99m (140 KeV) of $\left(\frac{\mu}{\rho}\right)_{lead} = 2.39 \left[\frac{\text{cm}^2}{\text{g}}\right]$ and $\left(\frac{\mu}{\rho}\right)_{Concrete} = 0.1495 \left[\frac{\text{cm}^2}{\text{g}}\right]$, and multiplied by the respective values of density exposed in item 3.2 we obtain:

$\mu_{Concrete} = 0.343\ \text{cm}^{-1}$ and $\mu_{lead} = 27.24\ \text{cm}^{-1}$

Table 6 Transmission factors for each point of interest.

Gamma chamber – Adjoining areas			
Wall	Total dose (mSv/year)	Dose restriction (mSv/year)	Transmission factor (B)
A	6.67	5	0.740
B	6.67	0.3	1.480
C	9.73	0.3	0.154
D	4.96	5	2.015
Incorporation room – Adjoining areas			
Wall	Total dose (mSv/year)	Dose restriction (mSv/year)	Transmission factor
D	18.57	5	0.269
E	5.78	0.3	0.052
F	37.14	0.3	0.008
G	2.67	0.3	0.112

Table 7 Concrete and lead wall thicknesses that satisfy the shielding need according to transmission factors B.

Gamma chamber – Adjoining areas		
Wall	Lead thickness (mm)	Concrete thickness (cm)
A	0.11	0.86
B	-0.14 (NR)	-1.12 (NR)
C	0.67	5.36
D	-0.25 (NR)	-2.01 (NR)
Incorporation and rest room – Adjoining areas		
Wall	Lead thickness (mm)	Concrete thickness (cm)
D	0.47	3.76
E	1.07	8.48
F	1.74	13.81
G	0.79	6.27

NR= Not Required

Table 8 Necessary shielding thickness using lead or concrete, assuming occupancy factors 1 for all points of interest.

Gamma chamber – Adjoining areas		
Wall	Lead thickness (mm)	Concrete thickness (cm)
A	0.11	0.86
B	1.12	8.93
C	1.25	9.97
D	0 (NR)	-0.02 (NR)
Incorporation and rest room – Adjoining areas		
Wall	Lead thickness (mm)	Concrete thickness (cm)
D	0.72	5.75
E	1.65	13.09
F	1.74	13.81
G	1.37	10.88

Table 9 Shielding thicknesses obtained from the attenuation factor method.

Gamma chamber – Adjoining areas		
Wall	Lead thickness (mm)	Concrete thickness (cm)
A	0.11	0.88
B	-0.14 (NR)	-1.14 (NR)
C	0.69	5.45
D	-0.26 (NR)	-2.04 (NR)
Incorporation and rest room – Adjoining areas		
Wall	Lead thickness (mm)	Concrete thickness (cm)
D	0.48	3.83
E	1.09	8.63
F	1.77	14.05
G	0.80	6.38

To determine thickness by using the linear attenuation factor obtained, we used equation (14). The results of thickness required for optimal shielding by using the attenuation factor method are shown in Table 9.

6. Conclusions

The total workload due to the manipulation of Tcm99 is greater in the incorporation room than in the Gamma chamber; this is principally because the permanence time of patients there is higher than their passage through the Gamma chamber. Activities carried out in the incorporation room are -injecting radioactive material – patient's rest – stress test.

Upon comparing Tables 7 and 9, it can be concluded that the barrier's thickness calculations show no significant changes between both methods.

The shielding calculation is very sensitive to the correct selection of the parameters that modify the correction factors; for example, by being more conservative regarding the occupancy factor granting all the areas the value of 1, the shielding thicknesses increase considerably, which is reflected when comparing Tables 6 and 7. Shielding increase by 74% is evidenced for wall G.

It is important to define follow-up protocols to the shielding conditions, given that modifications in the environments, increased number of patients, etc., attempt against radiological security in institutions.

The area of interest requiring the greatest care regarding the shielding demand is the wall in the incorporation room that adjoins the reception, whose thickness in Pb yields a value of 1.77 mm, according to Table 9. The areas where no special shielding is required are associated to the walls of the Gamma chamber that next to the parking lot and the incorporation room. The distance factor between the source and the point of interest takes on an important value.

References

[1] ICRP, "ICRP Publication 86. Prevention of accidental exposures to patients undergoing radiation therapy. A report of the International Commission on Radiological Protection," *Ann. ICRP*, vol. 30, no. 3, pp. 7–70, 2000.

[2] C. Chiesa, V. De Sanctis, F. Crippa, and M. Schiavini, "Radiation dose to technicians per nuclear medicine procedure: comparison between technetium-99m, gallium-67, and iodine-131 radiotracers and fluorine-18," *Eur. J. Nucl. Med.*, vol. 24, no. 11, pp. 1380–1389, 1997.

[3] F. A. Mettler Jr and M. J. Guiberteau, *Essentials of nuclear medicine imaging*. Elsevier Health Sciences, 2011.

[4] B. M. Methe, "Shielding design for a PET imaging suite: a case study," *Health Phys.*, vol. 84, no. 5, pp. S83–S88, 2003.

[5] E. Smith, "Properties, uses, radiochemical purity and calibration of Tc99m," *J. Nucl. Med.*, no. 5:871–882, 1964.

[6] I. Zolle, H. Spies, H.-J. Pietzsch, E. Chiotellis, Z. Kovács, O. Bremer, and G. Jánoki, *Technetium-99m Pharmaceuticals: Preparation and Quality Control in Nuclear Medicine*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007.

[7] H. C. Hoyt and J. W. M. DuMond, "Gamma Radiation Following Decay of I 131," *Phys. Rev.*, vol. 91, no. 4, pp. 1027–1027, Aug. 1953.

[8] M. R. A. Pillai, S. Chakraborty, T. Das, M. Venkatesh, and N. Ramamoorthy, "Production logistics of 177 Lu for radionuclide therapy," *Appl. Radiat. Isot.*, vol. 59, no. 2, pp. 109–118, 2003.

[9] Autoridad Regulatoria Nuclear, *Norma básica de seguridad radiológica*, no. AR 10.1.1. Argentina, 2003.

[10] J. Valentin, "ICRP Publication 103. The 2007 recommendations of the international commission on radiological protection," *Ann. ICRP*, vol. 37, no. 2–4, 2007.

[11] C. Varela, M. Díaz, G. M. López, L. A. Torres, M. A. Coca, and J. González, "Aplicación regulatoria de criterios de calidad a la instrumentación de Medicina Nuclear," *Tc*, vol. 32, no. 51Cr, p. 192Ir, 2008.

[12] NCRP, "NCRP Report No. 151 - Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities," 2005.

[13] K. D. Steidley, "NCRP Report No. 49: Structural Shielding Design And Evaluation For Medical Use Of X-Rays And Gamma Rays Of Energies Up To 10 MeV," *J. Nucl. Med. Technol.*, vol. 5, no. 2, p. 107, 1977.

[14] D. L. Miller, E. Vañó, G. Bartal, S. Balter, R. Dixon, R. Padovani, B. Schueler, J. F. Cardella, and T. De Baère, "Occupational radiation protection in interventional radiology: a joint guideline

of the Cardiovascular and Interventional Radiology Society of Europe and the Society of Interventional Radiology," *Cardiovasc. Intervent. Radiol.*, vol. 33, no. 2, pp. 230–239, 2010.

[15] FAO, IAEA, ILO, OECD/NEA, PAHO, and WHO, "Safety Series No. 115: International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources." IAEA, Vienna, 1996.

[16] F. A. Mettler Jr, W. Huda, T. T. Yoshizumi, and M. Mahesh, "Effective doses in radiology and diagnostic nuclear medicine: a catalog 1," *Radiology*, vol. 248, no. 1, pp. 254–263, 2008.

[17] M. M. Ninkovic, J. J. Raicevic, and F. Adrovic, "Air kerma rate constants for gamma emitters used most often in practice," *Radiat. Prot. Dosimetry*, vol. 115, no. 1–4, pp. 247–250, 2005.

[18] H. Wasserman and W. Groenewald, "Air kerma rate constants for radionuclides," *Eur. J. Nucl. Med.*, vol. 14, no. 11, pp. 569–571, 1988.

[19] A. McNair, "Radiation Quantities and Units: International Commission on Radiation Units and Measurements ICRU Report 33," John Wiley & Sons, Ltd., Washington D.C. USA, Sep. 1981.

[20] H. E. Johns and J. R. Cunningham, *The Physics of Radiology*, 3rd ed. Springfield, Illinois, USA: C.C. Thomas, 1969.

[21] M. Núñez, "Control de calidad de los sistemas de detecci{ó}n usados en Medicina Nuclear," *Esc. Univ. Tecnol. M{é}dica. UdelaR, Montevideo, Uruguay. Com. Tecn{ó}logos ALASBIMN*, 2008.

[22] NIST, "X-Ray Mass Attenuation Coefficients," *NIST*. [Online]. Available: http://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/concrete.html.

[23] B. Lauridsen, "Table of Exposure Rate Constants and Dose Equivalent Rate Constants," Roskilde, 1982.

[24] K. Eckerman and A. Endo, "ICRP Publication 107. Nuclear decay data for dosimetric calculations.," *Ann. ICRP*, vol. 38, no. 3, pp. 7–96, 2008.

[25] L. M. Unger and D. K. Trubey, "Specific gamma-ray dose constants for nuclides important to dosimetry and radiological assessment," Tennessee, United States, 1982.

[26] W. A. Volkert, W. F. Goeckeler, G. J. Ehrhardt, and A. R. Ketring, "Therapeutic radionuclides: production and decay property considerations.," *J. Nucl. Med. Off. Publ. Soc. Nucl. Med.*, vol. 32, no. 1, pp. 174–185, 1991.

[27] E. B. Podgorsak, *Radiation oncology physics: a handbook for teachers and students*. Vienna: IAEA, 2005.

[28] Y. Yi, M. G. Stabin, M. H. McKaskle, M. D. Shone, and A. B. Johnson, "Comparison of measured and calculated dose rates near nuclear medicine patients," *Health Phys.*, vol. 105, no. 2, pp. 187–191, 2013.

[29] B. Archer, J. Thornby, and S. Bushong, "Diagnostic X-ray shielding design based on an empirical model of photon attenuation.," *Health Phys.*, 1983.

[30] D. J. Simpkin and R. L. Dixon, "Secondary shielding barriers for diagnostic x-ray facilities: scatter and leakage revisited.," *Health Phys.*, vol. 74, no. 3, pp. 350–365, 1998.

[31] S. Ivanova and A. Artinyan, "Calculations and Analysis of the Radiation Protection of PET/CT Center," *BgNS Trans.*, 2015.

[32] M. W. Groch and W. D. Erwin, "SPECT in the year 2000: basic principles.," *J. Nucl. Med. Technol.*, vol. 28, no. 4, pp. 233–244, 2000.

[33] M. Bocher, A. Balan, Y. Krausz, Y. Shrem, A. Lonn, M. Wilk, and R. Chisin, "Gamma camera-mounted anatomical X-ray tomography: technology, system characteristics and first images," *Eur. J. Nucl. Med.*, vol. 27, no. 6, pp. 619–627, 2000.

[34] M. Madsen, J. Anderson, J. Halama, and J. Kleck, "AAPM task group 108: PET and PET/CT shielding requirements," *Med. Phys.*, vol. 33, no. 1, pp. 4–15, 2006.

[35] H. Remy, I. Borget, S. Leboulleux, N. Guilabert, F. Lavielle, J. Garsi, C. Bournaud, S. Gupta, M. Schlumberger, and M. Ricard, "131I effective half-life and dosimetry in thyroid cancer patients," *J. Nucl. Med.*, vol. 49, no. 9, pp. 1445–1450, 2008.

[36] J. G. McAfee, C. F. Fueger, H. S. Stern, H. N. Wagner, and T. Migita, "Tc99m pertechnetate for brain scanning," *J. Nucl. Med.*, vol. 5, no. 11, pp. 811–827, 1964.

[37] ARN, "Norma básica de seguridad radiológica. Boletín Oficial No. 20/11/01," Argentina, 2001.

[38] ICRP, "ICRP Publication 60. 1990 Recommendations of the International Commission on Radiological Protection," *Ann. ICRP*, vol. 21, no. 1–3, 1991.

[39] OIEA, "Aspectos físicos de la garantía de calidad en radioterapia: Protocolo de control de calidad." OIEA, Viena, Austria, 2000.

[40] N. Singh, K. J. Singh, K. Singh, and H. Singh, "Comparative study of lead borate and bismuth lead borate glass systems as gamma-radiation shielding materials," *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 225, no. 3, pp. 305–309, 2004.

[41] B. R. Archer, T. R. Fewell, B. J. Conway, and P. W. Quinn, "Attenuation properties of diagnostic x-ray shielding materials," *Med. Phys.*, vol. 21, no. 9, pp. 1499–1507, 1994.

[42] NCHPS, "North Carolina Chapter of the Health Physics Society (NCHPS)." [Online]. Available: http://hpschapters.org/northcarolina/nuclide_information_library.php3. [Accessed: 06-Sep-2010].

[43] I. Balseiro, "Sistema de Protección para la Radiación Externa." [Online]. Available: http://www.ib.cnea.gov.ar/~protrad/biblioteca/Blindajes de Fuentes Radiactivas.pdf. [Accessed: 08-Sep-2010].

[44] NIST, "National Institute Standards and Technology." [Online]. Available: http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html. [Accessed: 09-Sep-2010].

[45] U. of M. Occupational Safety & Environmental Health, "Technetium - 99m." University of Michigan, 1994.

[46] NCRP, "Report No. 147 - Structural shielding design for medical X-ray imaging facilities.," National Council on Radiation Protection and Measurement, 2004.

[47] J. H. Hubbell and S. M. Seltzer, "Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 meV for elements z = 1 to 92 and 48 additional substances of dosimetric interest," 1995.

[48] J. Maddahi, H. Kiat, K. F. Van Train, F. Prigent, J. Friedman, E. V Garcia, N. Alazraki, E. G. DePuey, K. Nichols, and D. S. Berman, "Myocardial perfusion imaging with technetium-99m sestamibi SPECT in the evaluation of coronary artery disease," *Am. J. Cardiol.*, vol. 66, no. 13, pp. E55–E62, 1990.

[49] E. G. DePuey, K. Nichols, and C. Dobrinsky, "Left ventricular ejection fraction assessed from gated technetium-99m-sestamibi SPECT.," *J. Nucl. Med. Off. Publ. Soc. Nucl. Med.*, vol. 34, no. 11, pp. 1871–1876, 1993.

[50] M. D. M. D. V. Torres, A. L. G. Cardo, S. J. O. Lozano, and J. M. J.-H. Garc'\ia, "Técnicas de imagen en el diagnóstico de metástasis óseas: Imaging techniques in the evaluation of metastatic bone disease," *Rev. Española Med. Nucl.*, vol. 26, no. 4, pp. 237–258, 2007.