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Simple approach to evaluate safety requirements to establish nuclear cardiology unit: Shielding and Occupational dose calculations

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TECHNETIUM-99M sestamibi (MIBI), or 99mTc-methoxy isobutyl isonitrile, is a radiopharmaceutical used for assessing cardiac pathologies. 99mTc belongs to the category of radioactive diagnostic agents. The goal of the present study is to firstly; develop a plan for determining shielding and occupational doses in a nuclear cardiology facility when using 99mTc MIBI as a radiopharmaceutical, secondly; ensuring the safety of radiation for both healthcare workers as well as general public. Using precise radiation protection equations, the necessary thickness of lead and concrete shielding was determined for different areas in a simulated unit for nuclear cardiology based on the interior design provided. Calculations were conducted for regions where staff are regularly present, and with areas accessible to the general public. **Results:** A Lead shield thickness of 0.23 mm to 1.27 mm or a concrete thickness of 4.65 cm to 16.12 cm were found necessary to keep radiation exposure below dose constraints 0.3 mSv per year for public and 5 mSv per year for radiation workers, at the imaging and corporation rooms walls. Our calculations also showed that, with these protective measures in place, the highest annual occupational dose for workers was 1.81 mSv, well below the international safety limit of 20 mSv per year. **Conclusions:** The present study offers a straightforward, pragmatic method for calculating shielding and occupational doses in nuclear cardiology. The findings guarantee adherence to global safety regulations, providing valuable advice for medical facilities seeking to create or enhance their nuclear cardiology services.

Keywords: Nuclear cardiology, Radiation shielding, Occupational dose, Syringe shield, shielding tools, Safety protocols.

Introduction

The widespread application of nuclear-cardiology techniques for diagnosing cardiac diseases could lead to an increase in the incidence of radiation exposure of medical staff and the public [1]. Nuclear cardiology is a branch of nuclear medicine that assesses myocardium viability and heart functions [2]. This specialty utilizes radioactive materials, known as radio pharmaceuticals, to provide critical insights into cardiovascular health. Given the inherent risks associated with the use of these materials [2,3], it is essential to implement stringent safety protocols to protect both healthcare professionals and patients. Regulatory bodies such as the Nuclear Regulatory Commission (NCRP) and the International Commission on Radiation Protection (ICRP) have established comprehensive standards governing the handling, administration, and disposal of radio-pharmaceuticals, emphasizing the importance of adherence to these guidelines to mitigate potential hazards [4,5].

Nuclear medicine unit requires shielding studies and security requirements**.** The International Atomic Energy Agency (IAEA) recommends a dose rate below 20 mSv/year for workers and 1 mSv/year for the public. The IAEA also recommends annual dose restrictions for controlled zones (hot lab, incorporation room, gamma camera control room and imaging room) and uncontrolled zones (reception-room, patients preparation room, physician room, and the companions waiting room) [6-9]. The cardiac study is a two-day protocol where procedures involve exercise on a treadmill machine, injection of ^{99m}Tc Methoxy-IsoButyl-Isonitrile (^{99m}Tc MIBI), rest in rest room (incorporation room), and imaging in the gamma camera room after one hour incorporation time. Patients are then informed about the date of the resting study where the same procedures are repeated without exercise and then the patient is dismissed with instructions on how to deal with family members and the public during the next 24 hours.

To ensure compliance with safety regulations, healthcare providers must obtain authorized user (AU) status, which involves completing specialized training and demonstrating competence in radiation safety practices [5]. There has been a lack of knowledge regarding the need for shielding calculation in Nuclear Medicine services [10,11]. This paper outlines a detailed methodology for evaluating safety requirements in the establishment of a nuclear cardiology unit, emphasis on radiation shielding and occupational dose management. This method takes into account the multiple energies of ^{99m}Tc [12] and clears the confusion about which scientific tools must be used to calculate the dose absorbed by the public and different worker from the radio-active patient and the methods to accurately calculate the shielding materials specifications [10,13,14]. To ensure public safety, the radioactive patient dose rate calculation (for a period of hours) after the patient's dismissal is introduced [1].

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This work aims to enhance safety protocols in nuclear cardiology, ensuring the well-being of healthcare professionals and patients alike.

Material and methods

I. Shielding Calculations

Calculations for shielding “Using point source geometry” began with the fundamental formula for gamma radiation released by commonly utilized radiopharmaceuticals in nuclear cardiology, ^{99m}Tc MIBI. The weekly workload is assessed [7,15-17], then converted into the annual equivalent absorbed dose to soft tissue by taking into account the absorbed dose fraction specific to the patient's body [18,19]. The following step involves assessing the ratio of the dose constraint to the computed absorbed dose, known as the transmission factor B, which is then used to determine the required barrier thickness. This calculation employs the Archer fitting parameter for materials such as lead and concrete at an energy level of 140 keV. [13,14]. When utilizing protective barriers such as personal lead equivalent apron, lead, tungsten syringe shield, or concrete barrier, we apply the linear attenuation coefficients for lead, tungsten, and concrete at 140 KeV along with the material buildup factor, to evaluate the effect of the specific shield on radiation dose [20,21].

II. Occupational Dose calculation

Calculations were conducted in the working area to evaluate radiation exposure during regular nuclear cardiology procedures [7,9,15]. The sources of occupational dose were determined, hence the work load and the occupational absorbed dose was calculated depending on; work load, worker permanence time, distance from radiation source, and the applied shielding. We used occupancy factor T and use factor U each equaling 1, to maximize the radiation protection [7,22]. For calculating occupational doses at short distances ranging from 5 cm to 1 meter, we applied a line source geometry to achieve a more precise radiation dose assessment, effectively mitigating the inaccuracies introduced by the inverse square law of point source geometry. [23].

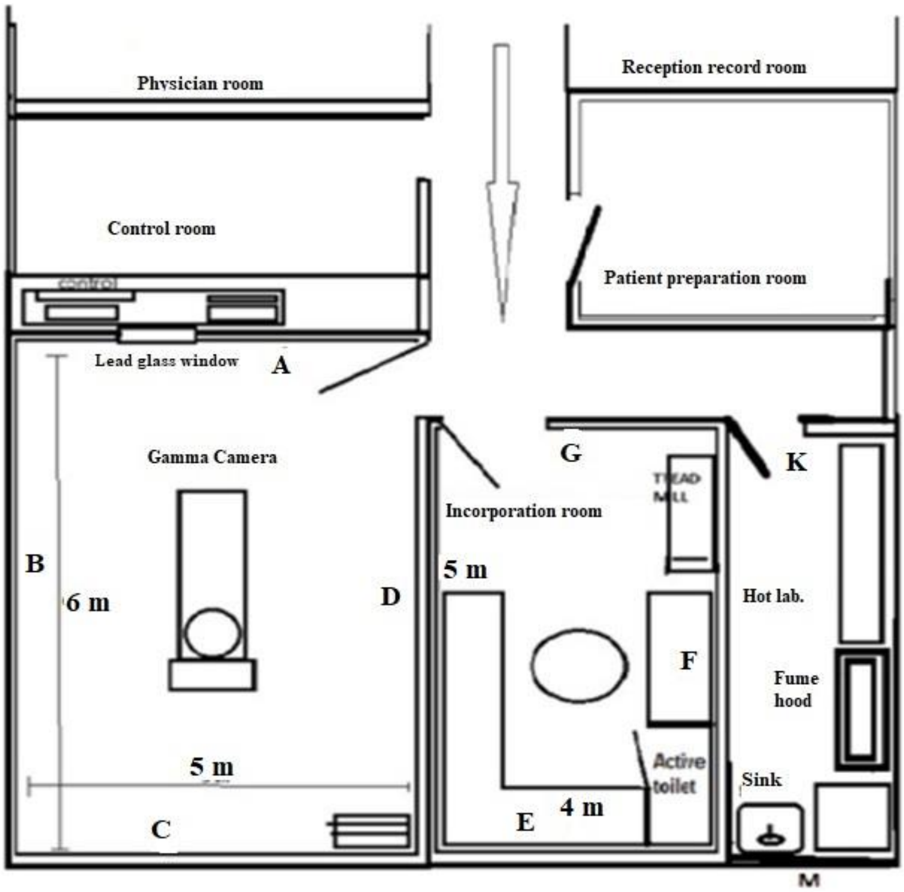

Fig. 1 Structural map of a Nuclear Cardiology unit.

Results

1- Shielding Calculation

Working zones in the nuclear medicine unit was Classified in to four sections (Fig. 1). (i) The incorporation room "also known as a resting room" is a controlled space with a 5 mSv/year dose restriction. (ii) The Hot lab. is a controlled and restricted space with a 5 mSv/year exposure limit. (iii) The Gamma Camera and its control room area are controlled and restricted areas with a 5 mSv/year dosage limit. (iv) The reception registration room, patient preparation room, and physician's office are uncontrolled spaces with a 0.3 mSv/y dosage restriction [7,24,25].

The basic equations for Shielding Calculation

The workload, W, indicates an approximation of the amount of radiation present in each area of the facility during a specific time interval [7,15-17].

$$W = \mathbf{D}_{\delta st} A N t_2 \qquad \textbf{(1) [17]}$$

Where: **A** maximum injected activity of ^{99m}Tc MIBI =1.11 GBq /patient; **N** number of patients per week = 50 patients; $\boldsymbol{t_2}$ defines the permanence time of the radionuclide in a given place of the facility in hours; $D_{\delta st}$ is the dose equivalent rate constant for soft tissue. For ^{99m}Tc; $D_{\delta st}$ = 16.1 µSv m^2/GBq h [13]

But due to patient effective body absorption factor of 0.364 for 140 keV photons calculated by ICRP report 23 [18,19], so that we will use $D_{\delta st}$ =10.24 µSv m^2/GBq h

2. Equivalent dose and correction factors

$$D_0 = \frac{W*T*U*R*F}{d^2} \text{ µSv/week} \qquad \textbf{(2) [26]}$$

Where: $\mathbf{D_0}$ absorbed equivalent dose for soft tissue, **T** occupancy factor**: *T* = 1.0 , U** use factor for natural source **= 1.0** [7,22], **d** is the distance from the (radioactive patient) to the point of interest under study at distance d, **R** Decay factor of ^{99m}Tc during permanence time t_2 and it is given by: [27,28]

$$\boldsymbol{R_{t2}} = \frac{\mathbf{1.44}\, T_{1/2}}{t_2}\left[\mathbf{1} - e^{-0.693\left(\frac{t_2}{T_{1/2}}\right)}\right] \qquad \textbf{(3) [27,28]}$$

Where: $\mathbf{t_2}$ is time spent by radioactive patient or a source at point of interest, $\mathbf{T_{1/2}}$ is physical half-life of ^{99m}Tc and its value is 6.02 hr .

Specific timing parameters preceded by "about", represent an overestimated assumption of the real time on average and should be followed as a monitoring guideline for the facility and might be changed according to the reality of the unit's situation (e.g. due changes in patient population/condition).

F is the Decay factor (F) after incorporating ^{99m}Tc MIBI and is given by: [10]

$$\boldsymbol{F} = e^{-0.693\left(\frac{t_1}{T_{\frac{1}{2}eff}}\right)} \qquad \textbf{(4)}$$

Where: $\mathbf{t_1}$ is the time between injection and arrival at point of interest, $\mathbf{T_{1/2\,eff}}$ is the effective half-life of ^{99m}Tc sestamibi = 4.8 hr [10]

To maximize protection level at any point of the calculation, we used the maximum value of patient dose (1.11 GBq) and occupation factor =1

Calculations of incorporation room dose rate

In this room the patient is injected with ^{99m}Tc MIBI dose. The injection time takes about 2 minutes (0.033 hr), the patient then rests for one hr So, t_2 = 1 hr + 0.033 hr = 1.033 hr

First we calculate work load in corporation room per week using eq. (1);

A maximum injected activity of ^{99m}Tc MIBI =1.11 GBq /patient

N number of patients = 50 patients/week, then:

$$\boldsymbol{W} = \mathbf{1}0.24\ x\ 1.11\ x\ 50\ x\ 1.033 = \mathbf{587.07}\ \mu\, Sv/week$$

Decay factor R_{t2} where $\mathbf{t_2}$, the patient's permanence time in rest room is 1.033 hr using eq. (3)

$$\boldsymbol{R_{t2}} = \frac{1.44*6.02}{1.033}\left[1 - e^{-0.693\left(\frac{1.033}{6.02}\right)}\right] = \mathbf{0.9408}$$

The radionuclide dose rate in the rest room, with time (t_2) using following equation [13]:

$$D_0 = \frac{W*T*U*Rt_2}{d^2} \text{µSv/week} \qquad \textbf{(5)}$$

Where **d,** is distance from (injected patients) to room walls in meter **(year=52 week)**

$$\boldsymbol{D_{0\,(1.033)}} = \frac{587.07456*1*1*0.9408*52}{d^2} = \frac{28722.75531}{d^2}\ \text{µSv/year}$$, see table 1.

Table 1. Incorporation room wall dose rate.

Incorporation room walls	Distance from patient in meter	Dose µSv/y	Dose mSv/y
D	2	7180.68	7.18068
E	2.5	4595.64	4.59564
F	2	7180.68	7.18068
G	2.5	4595.64	4.59564

Calculations of imaging room dose rate:
After one hr in the incorporation room, the patient goes to imaging room (gamma camera) where imaging procedures take about half hr in this room.
Where the permanence time of the (injected patient) in the imaging room is (t_2 **=0.5hr**).
(t_1) is the patient total radiopharmaceutical incorporating time = **1.533 hr** (0.033hr injection time +1 hr incorporation time + 0.5hr imaging time)
R_{t2} decay factor of ^{99m}Tc during imaging time (t_2 **=0.5hr**)
F_{t1} decay factor of ^{99m}Tc MIBI during patient radiopharmaceutical incorporating time (t_1=1.533hr)
$\boldsymbol{W} = 10.24 * 1.11 * 50 * 0.5 = \mathbf{28.416}$ µSv/week
Decay factor R_{t2} for imaging room where t_2 is imaging time **=0.5hr** using equation **(3)**

$$\boldsymbol{R_{t2}} = \frac{1.44 * 6.02}{0.5}\left[1 - e^{-0.693\left(\frac{0.5}{6.02}\right)}\right] = \mathbf{0.969744}$$

Decay factor F_{t1}**,** of ^{99m}Tc MIBI during patient radiopharmaceutical incorporating time. Using eq. **(4)**

$$\boldsymbol{F_{1.533}} = e^{-\ln 2\left(\frac{1.533}{T_{\frac{1}{2}eff}}\right)} = e^{-0.693\left(\frac{1.533}{4.8}\right)} = \mathbf{0.801417}$$

$$D_0 = \frac{W * T * U * Rt_2 * Ft_1}{d^2} \text{ µSv/week} \qquad \textbf{(6)}$$

Where **d** is the distance from (injected patients) to room walls in meter **(year=52 week),** The dose rate in the imaging room whose image time is (**0.5hr**)

$$\boldsymbol{D_{0\,(0.5)}} = \frac{284.16 * 1 * 1 * 0.801 * 52}{d^2} = \frac{11483.70}{d^2} \text{ µSv/year}$$, see table 2.

Table 2. Imaging room wall dose rate.

Imaging room walls	Distance from patient meter	Dose µSv/y	Dose mSv/y
A	3	1275.97	1.27597
B	2.5	1837.39	1.83739
C	3	1275.97	1.27597
D	2.5	1837.39	1.83739

Shielding calculation tools
1-To calculate shield thickness, we use the calculated transmission factor B (ratio of restricted dose to calculated dose) and Archer fitting parameter for lead and concrete at 140 KeV [13,14], see Table 3.
The Shield thickness formula is given by:

$$x = \frac{1}{\alpha * \gamma} \ln\left[\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right] \qquad \textbf{(7)}$$

The shield thickness unit is in mm for lead and in cm for concrete.

Table 3. fitting parameter for transmission factor for ^{99m}Tc [13].

Material	Archer parameters		
	α	**β**	**ɣ**
Lead in mm	2.479	-1.093	1.376
Concrete in cm	0.2813	-0.2349	0.9653

2- If the shield thickness is already present like lead equivalent apron, syringe shield or concrete barrier, we use the following equation that applies linear attenuation coefficients and buildup factor at 140 KeV to calculate the absorbed dose after the shield [27-30].

$$\boldsymbol{I} = I_o\, B_{XE}\, e^{-\mu x} \qquad \textbf{(8)}$$

Where: **I** radiation dose after applying shield, $\mathbf{I_0}$ radiation dose without shield, $\mathbf{B_{XE}}$ is the material's buildup factor for thickness x and energy E, **μ** is the linear attenuation coefficient for the shielding material.
To calculate the linear attenuation coefficient for lead, tungsten [31] and concrete we use the mass absorption coefficient, μ/ρ of them at 140 KeV multiplied by their density ρ [32,33]. That results in **μ** for lead =27.24 cm^{-1}, tungsten=36.28 cm^{-1} and concrete =0.343 cm^{-1}.
Table 4 and Table 5 provides the exposure buildup factor for lead, tungsten and concrete at 140KeV, in the form of mean free path (MFP) [20,21,34,35].

Table 4. Exposure buildup factor for lead and tungsten at 140 KeV [20,21,35].

MFP	LEAD Buildup Factor		MFP 1/27.24	LEAD Buildup Factor
0.5	1.33E+00		0.5	1.33E+00
1.0	1.53E+00		0.6	1.37E+00
2.0	1.79E+00		0.7	1.41E+00
3.0	1.98E+00		0.8	1.45E+00
4.0	2.14E+00		0.9	1.49E+00
5.0	2.29E+00		1.0	1.53E+00
5.2	2.32E+00		2.0	1.79E+00
5.4	2.35E+00		3.0	1.98E+00
5.6	2.38E+00		4.0	2.14E+00
5.8	2.41E+00		5.0	2.29E+00
6.0	2.44E+00			
7.0	2.62E+00			
8.0	2.82E+00			
8.2	2.87E+00			
8.4	2.92E+00			
8.6	2.96E+00			
8.8	3.01E+00			
9.0	3.06E+00			
10.0	3.35E+00			

Tungsten EBF

MFP	0.14 MeV
0.5	1.25E+00
1.0	1.34E+00
2.0	1.40E+00
3.0	1.42E+00
4.0	1.42E+00
5.0	1.43E+00
6.0	1.43E+00
7.0	1.44E+00
8.0	1.44E+00
9.0	1.44E+00
10.0	1.45E+00
15.0	1.46E+00
20.0	1.48E+00
25.0	1.49E+00
30.0	1.50E+00
35.0	1.51E+00
40.0	1.52E+00

Table 5. Exposure buildup factor for concrete [21].

MFP	0.4MeV	0.3MeV	0.2MeV	0.15MeV	0.14MeV	0.13MeV	0.12MeV	0.11MeV	0.1MeV
0.5 MFP	1.61E+00	1.68E+00	1.78E+00	1.84E+00	1.85E+00	1.85E+00	1.86E+00	1.87E+00	1.87E+00
1MFP	2.38E+00	2.52E+00	2.72E+00	2.81E+00	2.80E+00	2.80E+00	2.78E+00	2.78E+00	2.76E+00
2MFP	4.31E+00	4.66E+00	5.05E+00	5.13E+00	5.03E+00	4.93E+00	4.85E+00	4.74E+00	4.63E+00
3MFP	6.80E+00	7.43E+00	8.01E+00	7.91E+00	7.65E+00	7.41E+00	7.15E+00	6.91E+00	6.62E+00
4MFP	9.85E+00	1.09E+01	1.16E+01	1.12E+01	1.07E+01	1.02E+01	9.73E+00	9.26E+00	8.78E+00
5MFP	1.35E+01	1.50E+01	1.59E+01	1.50E+01	1.42E+01	1.34E+01	1.26E+01	1.19E+01	1.11E+01
6MFP	1.78E+01	1.99E+01	2.10E+01	1.93E+01	1.81E+01	1.70E+01	1.59E+01	1.48E+01	1.36E+01
7MFP	2.28E+01	2.56E+01	2.68E+01	2.42E+01	2.23E+01	2.06E+01	1.91E+01	1.77E+01	1.63E+01
8MFP	2.85E+01	3.22E+01	3.35E+01	2.96E+01	2.73E+01	2.51E+01	2.30E+01	2.10E+01	1.92E+01
9MFP	3.49E+01	3.97E+01	4.12E+01	3.58E+01	3.27E+01	2.99E+01	2.71E+01	2.46E+01	2.22E+01
10MFP	4.21E+01	4.82E+01	4.98E+01	4.25E+01	3.87E+01	3.51E+01	3.17E+01	2.86E+01	2.55E+01

Hot lab. Calculations

The procedure for preparing a patient's ^{99m}Tc MIBI syringe dose:

The storage of the radionuclide source (^{99m}Tc generator) exists under a fume hood with double cabinet each with 10 mm lead shield thickness. The preparation of ^{99m}Tc MIBI vial is done inside the fume hood with walls thickness of 10 mm of lead. 15 GBq milked sodium pretechnetate is added to the MIBI vail within a 3mm lead shield and kept in a boiling water bath for 10 minutes then let to cool down. The Half-Value Layer (HVL / Lead) = 0.27 mm (140 keV) [32,36,37] and the Tenth value layer (TVL/Lead) = 1.08 mm (140 KeV) [13,38,39]. The dose measurement is done with a dose calibrator protected by an L shape shield with lead thickness 10 mm. Syringe with 2mm lead shield withdraws 1.11 GBq ^{99m}Tc MIBI from the prepared ^{99m}Tc MIBI vial [40].

The patient dose is delivered to the injection site in the incorporation room within a syringe shielded with 2mm lead syringe shield, carried by a lead box with thickness 3 mm thick lead shield and a movable top.

The patient syringe dose spends about one minute in the hot lab. until it reaches incorporation room to be injected.

So, t =1 minute = 0.0166 hr for the hot lab, Each syringe carrying 1.11 GBq ^{99m}Tc MIBI, dose equivalent rate constant for ^{99m}Tc =16.1 µSv/GBq h

There is no reduction in equivalent absorbed dose rate constant because we deal with the radiation dose before injecting it in the patient, so there is no patient specific absorbed dose fraction effect.

Number of patient doses prepared weekly are 50 syringe doses. We will calculate dose rate at the walls of the hot laboratory, with and without accounting for the syringe shield.

1-Calculation of dose rate without syringe shield:

1.a The hot lab work load **W** using eq. (1), where $\mathbf{t_2}$= 1min. =0.0166 hr

$$\boldsymbol{W} = 16.1 * 1.11 * 50 * 0.0166 = \mathbf{14.83}\ \mu\boldsymbol{Sv}/\text{week}$$

1.b calculating decay factor using eq. (3)

$$R_{t2} = \frac{1.44 * 6.02}{0.0166}\left[1 - e^{-0.693\left(\frac{0.0166}{6.02}\right)}\right] = 0.99697$$

1.c calculating dose rate at hot lab. using eq. (5)

$$\boldsymbol{D}_{\mathbf{0}\,(\mathbf{0.016})} = \frac{14.83293*1*1*0.99697*52}{d^2} = \frac{768.97}{d^2}\ \mu\text{Sv/year}$$, see Table 6.

Table 6. Hot lab wall dose rate without syringe shield.

Hot lab walls dose	Distance from Syringe in meter	Dose µSv/year	Dose mSv/year
K	2.5	123.04	0.12304
F	1.5	341.77	0.34177
M	2.5	123.04	0.12304
H	1.5	341.77	0.34177

2-Dose rate with syringe shielding 2mm lead

Using eq. (8): Where, **I**, dose after shielding, $\mathbf{I_0}$ dose before shielding

µ attenuation coefficient of lead =27.24 cm^{-1} , and **x** is the thickness of shield in cm

Using 2mm lead syringe shield; 2mm lead =0.2 /(1/µ) =0.2/0.0367=5.4 MFP

$\boldsymbol{I} = \boldsymbol{I_o}\, \boldsymbol{B_{XE}}\, \boldsymbol{e}^{-(27.24*0.2)}$ **,** (B_{xe}= 2.35 for 5.4 MFP) from table 4:

at walls K and M:

$$\boldsymbol{I} = \boldsymbol{I_o}\, \boldsymbol{B_{XE}}\, \boldsymbol{e}^{-(27.24*0.2)} = 123.0357\,(2.35)\boldsymbol{e}^{-(27.24*0.2)} = \mathbf{1.24469412}\ \mu\text{Sv/y}$$

at walls F and H:

$$\boldsymbol{I} = I_o\, B_{XE}\, e^{-(27.24*0.2)} = 341.7658\,(2.35)\, e^{-(27.24*0.2)} = \mathbf{3.457483667}\ \mu\text{Sv/y}$$, see Table 7.

Table 7. Hot lab wall dose rate without and with syringe shield 2mm lead.

Hot lab. walls dose	Distance from Syringe	Dose without syringe shield µSv	dose with 2 mm lead shield µSv/year	dose with 2 mm lead shield mSv/year
K	2.5	123.04	1.24	0.00124
F	1.5	341.77	3.46	0.00346
M	2.5	123.04	1.24	0.00124
H	1.5	341.77	3.46	0.00035

The radiation dose rate at hot lab. walls is largely diminished compared to the recommended restriction limits (0.3 mSv/year), due to using shields like fume hood with 10mm lead wall and syringe shield with 2mm lead thickness. Usually, hot laboratory walls are covered with 3mm lead sheets.

A.3. We use transmission factor B to calculate barrier thickness:

B factor represents the required relative decline in the annual dose rate due to shielding. Where B is the ratio between the annual dose rate at a given distance with shielding system that achieving dose restriction **D** and the annual dose rate in the same point without shielding $\mathbf{D_0}$ [13,17,22].

$$\boldsymbol{B} = \frac{D}{D_o} \qquad (12)$$

Where **D** is the recommended restricted radiation dose at point of interest, $\mathbf{D_0}$ is the calculated radiation dose at the same point based solely on the distance of the walls from the patient. We used Archer model and Archer fitting parameter for ^{99m}Tc for lead and concrete [13,14,22] with the transmission factor to calculate shield thickness, Table (8).

For walls that have annual dose far less than the restriction dose, there is no need for more shielding. Walls B, C, G, and E adjoin public passes, so we use a restricted annual dose of 0.3 mSv/y. The hot lab. wall dose is severely under dose constraint values and already covered by 3mm lead.

Activity prior to syringe preparation (generator milking and ^{99m}Tc MIBI preparation), although it takes about 30 minutes, but the worker involvement in these activities is only few seconds. These activities are done inside the 10mm lead shielded fume hood with shielded vial container range from 3mm to 10mm lead and L shape shield with 10mm lead thickness.

Table 8. Lead and Concrete wall thicknesses that satisfy the shielding needed according to transmission factors B using Archer fitting parameter equation (7).

Incorporation room wall Transmission factors					
wall	**Annual dose rate (mSv)**	**Dose restriction (mSv/y)**	**Transmission factors**	**Lead thickness mm (mm)**	**concrete thickness in cm**
D	**7.181**	**5**	**0.696**	**0.23**	**4.65**
E	**4.596**	**0.3**	**0.0653**	**1.27**	**16.12**
F	**7.181**	**5**	**0.696**	**0.23**	**4.65**
G	**4.596**	**0.3**	**0.0653**	**1.27**	**16.12**
Imaging room wall Transmission factors					
wall	**Annual dose rate (mSv)**	**Dose restriction (mSv/y)**	**Transmission factors**	**Lead thickness (mm)**	**Concrete thickness cm**
A	**1.276**	**5**	**3.92**	**No need**	**No need**
B	**1.837**	**0.3**	**0.163**	**0.89**	**12.5**
C	**1.276**	**0.3**	**0.235**	**0.74**	**10.9**
D	**1.837**	**5**	**2.722**	**No need**	**No need**

Occupational dose rate at nuclear cardiology unit

Source of worker radiation dose

1-Dose from patient injections

A-From hot lab where shielded patient syringe dose lasts for 1min =0.0166 hr at 5 cm distance from workers' hand and 30 cm from workers' body.

B-From injection site in the incorporation room, where it lasts for t= 2min = 0.033 hr at one-meter distance from the patient who then becomes the main source of radiation

2-Dose at imaging room

A- From positioning of the patient which lasts about 5 min = 0.083 hr at distance 1 m with 31^{o} angle from the patient couch.

B-The dose received during the imaging procedure, t= 25 min =0.4166 hr at 3.6 meter in the control room behind wall (A) with a lead barrier of 2mm thickness.

Using Dose equivalent-rate constant for soft tissue equals 16.1 µSv/GBq h [13]

So, we will calculate the occupational dose using point source geometry and dose equivalent rate constant, then convert the results to line source geometry as a Function of Line-Source Length and Distance [23]

We will use the effective half-life of ^{99m}Tc MIBI 4.8 hrs [10] and physical half-life of ^{99m}Tc equal 6.02 hrs, linear attenuation coefficient of lead =27.24 cm^{-1} [32-33].

But we will use dose equivalent rate constant =10.24 µSv/GBq h, when dealing with radio-active patient due to patient body specific energy absorption fraction [18,19].

1-Calculation of workers' dose rate from hot lab. for hands and worker body: [15,16-26,27,28]

A- from hot lab.

workers hand: -

0ne min. t_2 = 0.0166 d= 5 cm = 0.05 meter, patient dose=1.11GBq, patients number=50

$$W = 16.1 * 1.11 * 50 * 0.016 = \mathbf{14.8329}\ \mu Sv/week$$

$$R_{t2} = \frac{1.44 * 6.02}{0.0166}\left[1 - e^{-0.693\left(\frac{0.0166}{6.02}\right)}\right] = \mathbf{0.99697}$$

$D_{0(0.016)} = \frac{14.8329 \text{ X1 X 1X } 0.99696 \text{ X } 52}{0.0025} = \mathbf{307589.23}$ µSv/y *without shield*

Using 2mm lead syringe shield: Using 2mm lead syringe shield: 2mm lead =0.2 /(1/µ) =0.2/0.0367=5.4 MFP eq. (9,10.11)

$\boldsymbol{I} = I_o\, B_{XE}\, e^{-(27.24*0.2)}$ **,** (B_{xe}= 2.35 for 5.4 MFP) from table 4 [20,21,29,30]

$$\boldsymbol{D_{0(0.016)}} = 307589.228\ (2.35)\ \boldsymbol{e}^{-(27.24*0.2)} = 3.11 \text{ mSv/y}$$

So that; *for workers' hand with syringe shield and 2mm lead shield* $\boldsymbol{D_{0(0.016)}}$***= 3.11mSv/y***

Workers body:

t=0.0166, d= 30 cm = 0.3 meter for worker body, then:

$D_{0(0.016)} = \frac{14.8329*1*1*0.99696*52}{0.09} = \mathbf{8544.15}$ **µSv/y ;** *without syringe shield*

Using 2mm lead syringe shield, 2mm lead thickness; then:

$\boldsymbol{I} = I_o\, B_{XE}\, e^{-(27.24*0.2)}$ **,** (B_{xe}= 2.35 for 5.4 MFP)

$\boldsymbol{D_{0(0.016)}} = 8544.15\ (2.35)\ \boldsymbol{e}^{-(27.24*0.2)} = \mathbf{86.44}$ µSv/y ; *with syringe shield*

Using 0.25mm lead equivalent personal apron shield: -

$\boldsymbol{I} = I_o\, B_{XE}\, e^{-(27.24*0.25)}$ **,** B_{xe}= 1.4 for 0.68 MFP, table (4)

$$\boldsymbol{D_{0(0.016)}} = 86.43709166\ (1.4)\ \boldsymbol{e}^{-(27.24*0.2)} = \mathbf{61.25}\,\mu\text{Sv/y}$$

$\mathbf{D_{0\,(0.016)}}$ **= 0.06** mSv/y with *syringe shield and apron*

B- From injection site

t_2 = 2 min = 0.033 hr d= 1 m from patient, using eq. (1,3and 5)

$$\boldsymbol{W} = 10.24 * 1.11 * 50 * 0.033 = \mathbf{18.75}\ \mu\boldsymbol{Sv/week}$$

$$R_{(0.033)} = \frac{1.44 * 6.02}{0.033}\left(1 - e^{-0.33\left(\frac{0.693}{6.02}\right)}\right) = 0.996027$$

$$D_{0(0.033)} = \frac{18.75 * 1 * 1 * 0.99602 * 52}{1^2} = \mathbf{971.36}\ \mu\mathbf{Sv/y}$$

$D_{0\,(0.033)}$ = 0.971 mSv/year *for workers' body at injection site*

Using 0.25mm lead equivalent personal apron shield, then:

$\boldsymbol{I} = I_o\, B_{XE}\, e^{-(27.24*0.25)}$ **,** B_{xe}= 1.4 for 0.68 MFP, table (4). eq. (9,10,11)

$\boldsymbol{D_{0(0.033)}} = 0.971\ (1.4)\ \boldsymbol{e}^{-(27.24*0.25)} = \mathbf{0.6883}$ **mSv/y;** *body with apron*

2-Dose at imaging room

A-due to patients positioning

$\mathbf{t_2}$ =5 min = 0.08 hr, at d =1m using eq. (1,3,4,6) [15,16,26-28]

$\mathbf{t_1}$ =1+0.033+0.083 =1.116 hr (incorporation time, injection time plus positioning time)

$$\boldsymbol{F_{1.116}} = e^{-ln2(\frac{t1}{T_{eff}})} = e^{-0.693(\frac{1.116}{4.8})} = \mathbf{0.8512}$$

t_2 = 0.083 hr for positioning only.

$$\boldsymbol{R}_{(0.083)} = \frac{1.44 * 6.02}{0.083}\left(1 - e^{-0.083(\frac{0.693}{6.02})}\right) = \mathbf{0.9931}$$

$$\boldsymbol{W} = 10.24 * 1.11 * 50 * 0.083 = 47.1706\ \mu\text{Sv/week}$$

$$D_{0p(1.083)} = \frac{47.1706 * 1 * 1 * 0.9931 * 0.8512 * 52}{1^2} = \mathbf{2073.52}\ \mu\mathbf{Sv/y}$$

Using 0.25mm lead equivalent personal apron shield; B_{XE}= 1.4 for 0.68 MFP

$\boldsymbol{D_{0p}}_{(1.116)} = 2.073\ (1.4)\ \boldsymbol{e}^{-(27.24*0.25)} = \mathbf{1.47mSv/y}$ **;** *due to positioning with apron*

B-The dose received during imaging procedure in control room using eq. (1,3,4 ,6)

t_2= 25 min =0.4166 hr, d= 3.6 m at wall (A) behind lead barrier 2mm thickness.

$$\boldsymbol{R_{t2}} = \frac{1.44\ (6.02)}{0.4166}\left(1 - e^{-\frac{0.4166\ (0.693)}{6.02}}\right) = \mathbf{0.9743}$$

$\mathbf{t_1}$=1.533 hr (injection time, incorporation time plus positioning times)

t_1=1+0.033+0.5=1.533 hr

$$F_{1.533} = e^{-ln2\ (\frac{t1}{T_{eff}})} = e^{-0.693\ (\frac{1.533}{4.8})} = \mathbf{0.80142}$$

Worker dose without shielding:

$$\boldsymbol{W} = 10.24 * 1.11 * 50 * 0.4166 = \mathbf{236.76}\ \mu Sv/week$$

$$D_{0(0.4166)} = \frac{236.762112 * 1 * 1 * 0.9743 * 0.80142 * 52}{3.6^2} = \mathbf{741.81}\ \mu\mathbf{Sv/y}$$

$\mathbf{D_{0\ (0.4166)}}$ **=0.74181 mSv/y** *due to imaging without barrier shield*

Using 2mm lead shield, B_{XE} = 2.35 for 5.4 MFP, then:

$$\boldsymbol{I} = \boldsymbol{I_o}\ \boldsymbol{B_{XE}}\ \boldsymbol{e}^{-(27.24*0.2)} = 0.7418\ (2.35)\boldsymbol{e}^{-(27.24*0.2)} = 0.00746\ \text{mSv/y; with 2mm lead barrier}$$

Then: $\boldsymbol{D_{0I}} = 0.7418\ (2.35)\boldsymbol{e}^{-(27.24*0.2)} = 0.00746\ \text{mSv/y; with 2mm lead barrier}$

Family and public absorbed dose from the patient

Using eq. 1 and 4 enables the calculation of family and public absorbed dose from the patient for example: - the patient leaves the unit after about 2.5 hr from the injection of ^{99m}Tc MIBI.

So, the dose rate at the time of injection $\mathbf{D_0}$=10.24x1.11=11.37 µSv /hr at one meter from the patient. After 2.5 hr post injection:

$$D_{2.5} = D_0\left(F_{2.5} = e^{-ln2\ (\frac{t2}{T_{eff}})}\right)$$

$$D_{2.5} = 11.37\ \left(e^{\frac{-0.693*2.5}{4.8}}\right) = \mathbf{7.92}\ \mu\mathbf{Sv/hr}$$

$\mathbf{D_{2.5}}$ **= 7.92 µSv/hr** at one meter from radioactive patient.

Dose constraint of gamma camera nuclear cardiology department

Dose rate at the department walls [6,7,8,9], see Table 9.

Occupational dose limits

Radioactive source: ^{99m}Tc with effective photon energy = 140.51KeV [41,42], and Half life time 6.02 hr. In radio-pharmaceutical form ^{99m}Tc MIBI with effective Half-Life$T_{1/2eff}$ 4.8 hr [10] Air kerma rate constant 14.24 µGy m^2/GBq h [38,39,43-46]. Absorbed dose rate constant 16.1 µSv m^2/GBq h [13,44,45].

Effective dose rate constant 12.78 µSv m^2/GBq h [47-49]

Unit usually consumes two Molybdenum ^{99m}Tc generator 55 GBq per month on average. See Table 10 and Table 11.

Table 11 declared that Worker hand equivalent dose is 0.271 mSv/y when converted to line source geometry to overcome the effect of inverse square law, the summation of Worker body equivalent dose is 0.0256+0.566+1.21+0.0074= 1.81 mSv/y.

Table 9. Dose rate at the department walls, shaded cells represent walls that adjoin public areas.

Unit walls	Annual dose rate (mSv/y)	Dose restriction (mSv/y)	Lead thickness to achieve dose restriction (mm)	Actually, wall lead thickness (mm)
A	**1.276**	5	No need	2
B	**1.837**	0.3	0.89	2
C	**1.276**	0.3	0.74	2
D	**7.181**	5	0.23	2
E	**4.596**	0.3	1.27	2
F	**7.181**	5	0.23	2
G	**4.596**	0.3	1.27	2
K	0.0012447 with syringe shield	0.3		3
F	0.00345748 with syringe shield	5		3
M	0.0012447 with syringe shield	0.3		3
H	0.00345748 with syringe shield	0.3		3

Table 10. Radioactive source and workload of the department.

	Patient				**worker**			
Radioactive source	Number / day	dose	Permanence / day	Total number / week	Number of technologists / day	Number of working day/w	Working time/day	Activity used/week
^{99m}Tc	8-10	1.11 GBq	1.533 hr	50±7	2	6	6 hr	55.5±8 GBq

Table 11. Occupational annual doses received by medical radiation worker, in nuclear cardiology department.

	point source calc.	**Point source correction factor to line source**	**Doses corrected to line source 174 cm**
Hand hot lab	3.11 mSv / y with syringe shield	0.087 for 5cm	0.271 mSv / y
Body hot lab	0.06mSv/y with syringe shield & apron	0.427 at 30 cm	0.0256 mSv / y
Body pt. injection	0.6883 mSv/year with apron	0.823 at 100 cm	0.566 mSv / y
Body pt. positioning	1.47mSv/y with apron	0.823 at 100 cm	1.21 mSv / y
Body pt. imaging	0.00746mSv/y 2mm lead shielding	The effect of inverse square law is diminished at 3.6 meter distance so no correction	0.00746 mSv/y

Discussion

Nuclear cardiology units need strong safety measures to protect against radiation risks. Using 99mTc MIBI for heart imaging creates challenges in radiation safety, that is why good shielding methods are important. The International Commission on Radiation Protection (ICRP) says workers should not get more than 20 mSv of radiation each year, which shows the need for proper shielding.

This study uses a careful method to figure out the right thickness for shielding in nuclear cardiology departments, looking at things like how fast radiation spreads and how well materials block it. It shows that using the right shielding materials can greatly lower radiation exposure. The study shows that the suggested shielding measures which range from 0.23 mm to 1.27 mm of lead or 4.65 cm to 16.12 cm of concrete for the room where radioactive materials are handled, and from 0.74 mm to 0.89 mm of lead or 10.9 cm to 12.5 cm of concrete for the imaging room successfully keep radiation exposure below the international safety limits of 5 mSv/year for workers and 0.3 mSv/year for the public in nearby areas. These results match the guidelines from the American Association of Physicists in Medicine (AAPM).

The impact of this research goes beyond just nuclear cardiology. It serves as a critical reference point for medical physicists and healthcare administrators striving to implement effective radiation protection measures across various medical specialties that utilize ionizing radiation. The methodologies outlined here can be adapted for other nuclear medicine applications, reinforcing the importance of tailored radiation safety protocols.

Moreover, as advancements in nuclear medicine technology continue, ongoing research into improved shielding materials and techniques will be vital. The study advocates for a culture of safety and continuous monitoring, highlighting that regular assessments of shielding effectiveness and occupational exposures are essential to adapt to evolving practices in nuclear medicine [9].

The evaluation of shielding requirements in nuclear cardiology is critical to ensuring the safety of both patients and healthcare personnel. This study utilized various methodologies to calculate the necessary shielding, including the assessment of lead and concrete wall thicknesses required to mitigate radiation exposure. The results indicate that specific thicknesses of lead and concrete can effectively reduce the transmission of gamma radiation, thereby protecting both occupational staff and patients from unnecessary exposure. The calculated transmission factors demonstrated that minimal shielding along with proper placement can significantly lower dose rates in controlled environments.

By incorporating the right equation in the right step, (e.g. line source model, MFP) we can achieve more accurate estimation of doses as well as emphasize the higher hazard zones to get the most benefit from shielding and spacing actions.

The study categorized working zones within a nuclear medicine unit based on occupancy and potential exposure, emphasizing the need for tailored safety protocols. Zones classified as "controlled" or "uncontrolled" require different shielding strategies, aligning with international recommendations. The study also found that dose rates without syringe shields were higher, emphasizing the need for protective measures. The findings suggest that design of spaces must consider radiation safety from the outset, ensuring adequate shielding and spacing. This detailed result is considered to be lower than the limits recommended by ICRP, NCRP&IAEA reports [5,7,24,25].

The occupational dose of technologists is determined by their daily activities, and increasing the number of technologists can reduce workloads. Shielding calculations aim to reduce radiation exposure, following guidelines from the IAEA and ICRP. The accuracy of these calculations depends on factors like occupancy factor, use factor, material linear attenuation, build up factor, and archer fitting parameters. The linear attenuation of materials in this study aligns with previous research. [17].

Estimating the barrier's attenuation using linear attenuation coefficients and exposure buildup factors for the radionuclide provides a more precise method compared to relying on TVL tables. The buildup factors were derived from geometric-progression fitting parameters and lead coherent scattering correction factors, as outlined in ANSI/ANS-6.4.3. To enable practical application, transmission curves were fitted to the mathematical model proposed by Archer et al. [22]. Attenuation is more accurately represented by the Archer fits [13,14]. Applying linear attenuation coefficient with exposure buildup factor provided by this work Shimizu et al. (2004) result in attenuation about 29% for pure lead thickness 0.25 mm due to scattered radiation from pure lead ^{99m}Tc the energy region of the gamma rays often exceeds the K absorption edge of lead (88 keV) and hence can give rise to characteristic lead X-rays, such as K α1 (74.97 keV), Kα2 (72.81 keV) and Kβ1 (84.94 keV) [50]. In reality many of the newer Pb aprons don't really contain Pb, but a mixture of various metals, all of which will result in different energy spectra that lead to about 50% intensity reduction.

This study utilizes the exposure buildup factor from Shimizu et al. (2004), as it employs the invariant embedding method, which enhances the accuracy of the ANS buildup factor data for materials such as iron, water, concrete, and lead. This approach extends the data to 100 mean free paths (mfp) and offers a more precise treatment of bremsstrahlung effects. Below 10 mfp, for photon energies ranging from 100 keV to 150 keV, the difference between Shimizu et al. and ANSI/ANS-6.4.3 is minimal [13]. The TVL calculations using the Archer fitting parameter in this study show excellent agreement, with only a 1% discrepancy compared to previous work [13].Using lead attenuation coefficient and exposure build up factor provided by this work to calculate the effect of lead shield 2mm thickness result in dose reduction about 98.99% of its initial value, using the same tool for 3mm lead thickness result in dose reduction about 99.99% of its initial values this results is in a good agreement with results of [38], where the difference is 5.6% for 3mm thickness.

The patient dose equivalent rate to soft tissue calculated in this study is 11.36 µSv/hr at one meter immediately after injection which it is in good agreement with recent study [51] According to their work, the main patient dose rate corresponding to administrated dose of 1.11 GBq of ^{99m}Tc MIBI is 12.19 µSv/hr at one meter ranging from 8.86 µSv/hr to 17.54µSv/hr at one meter.

The highest whole body occupational equivalent dose in our work resulted from patient positioning and it equal to 2.073 mSv/year without protective apron and 1.47 mSv/y with protective apron which in agreement with the results from [52]. The two works share the same patient number per week, the permanence time (5 minute) exposure, exposure distance (1 meter) and exposure angle with respect to patients' couch (31^0) but differ in the injected activity, where they use activity only more than (740 MBq). So, that result in average annual effective dose is 1.87 mSv/year.

Conclusion

The present study provides a framework for evaluating radiation shielding and occupational dose calculations in nuclear cardiology units using 99mTc MIBI as a radiopharmaceutical. It demonstrates precise calculations to ensure radiation exposure remains within international safety limits. The research serves as a guide for healthcare facilities to improve nuclear cardiology services, promoting safety and responsibility. It emphasizes continuous monitoring and assessment of radiation safety protocols. In conclusion, this study not only contributes to the existing body of knowledge in medical physics but also sets a precedent for future research aimed at refining safety protocols in nuclear medicine. The promotion of stringent safety measures in nuclear cardiology is vital, not just for regulatory compliance, but for enhancing public trust in the safety of medical imaging practices. This work underscores the critical role of radiation protection in advancing the field of medical physics and safeguarding health outcomes for both medical professionals and patients alike.

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طريقة بسيطة لتقييم متطلبات السلامة لإنشاء وحدة أمراض القلب النووية: حسابات الوقاية الإشعاعيه وجرعات العاملين في المجال الإشعاعي

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التكنيشيوم-99م سيستاميبي(^{99m}Tc MIBI) ، أو ميثوكسي إيزوبوتيل إيزونيتريل، هو عبارة عن مستحضر صيدلاني مشع يكثر استخدامه لأغراض تقييم أمراض القلب. ينتمي ^{99m}Tc إلى فئة العناصر المشعة المستخدمه في التشخيص الطبي. و الهدف من الدراسة الحالية هو أولاً؛ وضع خطة لتحديد جرعات الحماية والمهنية في منشأة أمراض القلب النووية عند استخدام ^{99m}Tc MIBI كمستحضر صيدلاني مشع، ثانيًا؛ ضمان السلامة من اضرار الإشعاع لكل من العاملين في مجال الرعاية الصحية وكذلك عامة الناس. و قد تم استخدام معادلات الحماية من الإشعاع الدقيقة، كما تم تحديد السُمك اللازم للدروع المصنوعة من الرصاص والخرسانة للمناطق المختلفة داخل وحدة محاكاة لطب القلب النووي بناءً على التصميم الداخلي المقدم. و قد تم الأخذ في الإعتبار اثناء الحسابات مجموعه من العوامل الهامه مثل ثوابت معدل الجرعة، وتراكم التعرض، ومعامل توهين المواد و ذلك من اجل الحفاظ على جرعات اشعاعيه ضمن الحدود المسموح بها و الآمنة. تم اجراء الحسابات للمناطق التي يتواجد فيها الموظفون في الوحده بشكل منتظم ، وكذلك المناطق التي يمكن الوصول إليها من قبل عامة الناس. و قد خلصت الحسابات الى أن استخدام سمك من عنصر الرصاص يتراوح بين 0.23 مم إلى 1.27 مم أو سمك من مادة الخرسانة الذي يتراوح بين 4.65 سم إلى 16.12 سم يضمن ان يكون التعرض للإشعاع في مناطق الغرف المستخدمة للتصوير الإشعاعي أقل من الحد المسموح به للتعرض للأشعاع سواء للعاملين في المجال الإشعاعي (5 مللي سيفرت سنويا) او بالنسبة للعامه من الناس (0.3 ميكروسيفرت سنويا). وأظهرت حساباتنا أيضًا أنه مع وضع هذه التدابير الوقائية، كانت أعلى جرعة مهنية سنوية للعمال 1.81 ميكروسيفرت، وهو أقل بكثير من حد الأمان الدولي البالغ 20 ميكروسيفرت سنويًا. و كخلاصه فان الدراسة الحالية تقدم طريقة مباشرة سهله وعملية لحساب جرعات الوقاية والجرعات المهنية في داخل وحدة طب القلب النووي. وتضمن النتائج الالتزام بلوائح السلامة العالمية، وقد توفر نصائح قيمة للمرافق الطبية التي تسعى إلى إنشاء أو تحسين خدمات طب القلب النووي.