

Evaluate Shielding Design of the Brachytherapy Unit by Using Monte Carlo Simulation Code

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Abstract

Shielding design is necessary for brachytherapy treatment room in order to protect the general public and employees. The main objective of this study was to investigate whether the protective unit of our Brachytherapy Centre provided adequate protection to the health and safety assessment of radiobiological impact. In this study, we estimated the effect of radiobiological protection from a single Ir-192 brachytherapy source in Brachytherapy center by using MCNP5 Monte Carlo measurements. The room was based on the design specifications for the HDR 192 Ir treatment was modeled. The estimated dose rate range for HDR 192 Ir and public buildings is (0.45 - 0.64): (micro sievert) $\mu\text{Sv}/\text{hour}$. Dose rates measured data for the current setup Brachytherapy HDR unit was approved and agreed quiet well with recommendation of International Atomic Energy Agency. The measured dose rate for public areas and controlled areas, compared with the reference value of 7.5 $\mu\text{Sv}/\text{h}$ and 0.5 $\mu\text{Sv}/\text{h}$ and concluded that we have enough shielding to the source but an over estimate with experimental measurements had been seen.

Keywords

Computer Codes and Modeling, Dose Equivalent, Effective Dose, Shielding, Monte Carlo Code System

1. Introduction

Monte Carlo N-Particle Transport Code (MCNP) is a software package for simulating nuclear processes. It is developed by Los Alamos National Laboratory since at least 1957 with several further major improvements [1].

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It is distributed within the United States by the Radiation Safety Information Computational Center in Oak Ridge, TN and internationally by the Nuclear Energy Agency in Paris, France. It is used primarily for the simulation of nuclear processes, such as fission, but has the capability to simulate particle interactions involving neutrons, photons, and electrons. "Specific areas of application include, but are not limited to, radiation protection and dosimetry, radiation shielding, radiotherapy, medical physics, nuclear criticality safety, detector design and analysis, nuclear oil well logging, accelerator target design, fission and fusion reactor design, decontamination and decommissioning." MCNPX (Monte Carlo N-Particle extended) is also developed at Los Alamos National Laboratory, and is capable of simulating particle interactions of 34 different types of particles (nucleons and ions) and 2000+ heavy ions at nearly all energies, including those simulated by MCNP [2]. Both codes can be used to judge whether or not nuclear systems are critical and to determine doses from sources, among other things. MCNP6 is a merger of MCNP5 and MCNPX [3]. The Monte Carlo code system MCNP is employed for the simulation. MCNP is a general purpose Monte Carlo radiation transport code which can simulate coupled neutron, and photo neutron transport in three dimensions through complex geometries is constructed as Boolean combinations of planes, spheres, cones and cylinders [4]. An energy cut off value of 1 KeV is used to terminate tracking of photon and electron histories. MCNP requires the source for a particular problem to be specified in a user-defined input file. The source includes distributions of the positions, energy and angle of the starting particles. The cross section library containing data from the ENDF is included with the MCNP code that is utilized for the computations [4]. In this study, we use MCNP5 simulation code. This code is suitable for such shielding investigation because of an extensive library of cross sections for materials that are use for shielding, and then compare the experimental calculations with MCNP5 simulation in occupied areas and verify whether the shielding provides adequate protection for the staff and the public in its current operational state and make appropriate recommendations to address any radiological health and safety hazards identified. Brachytherapy is a technique by which sealed radioactive sources are introduced into the body and positioned near the tumor using appropriate applicator devices. This technique can deliver the desired dose to the tumor while avoiding damage to healthy tissues. To achieve the best possible treatment planning, it is very important to know as precisely as possible the dose distribution around not only the source but also the applicator [5]. Specially designed rooms should have sufficient shielding to limit the treatment radiation exposure dose received by other patients, nursing staff and members of the public in the surrounding areas [6]. There are several sources for use in brachytherapy such as ^{131}I , ^{60}Co and ^{192}Ir [7]. Iridium-192 source at the Mahdieh Brachytherapy center is used for HDR (High Dose Rate) brachytherapy ^{192}Ir source use as after loading source with a half-life of 74 days, with a average gamma energy of about 0.38 MeV. Ir-192 with the activity between 2 - 12 Ci (Curie is a unit of radioactivity and radioactive materials to be used to express the activity of the audit) can be used as HDR source in Brachytherapy. The brachytherapy design depends on treatment techniques, work load, activity of the source, nuclides and energy of source. In brachytherapy, room and wall shielding designs must be sufficient to reduce the primary and scattered radiation since the sources are unshielded in all directions. Brachytherapy treatment rooms should comply with both national and international regulations that deal with shielding requirement to render an installation safe from radiation protection point of view [8]. For public areas and controlled areas, radiation should be in reference value range of $0.75\ \mu\text{Sv/h}$ and $0.5\ \mu\text{Sv/h}$ [9]. The design should also take into the best simulation code to evaluate the shielding adequacy [10]. Mahdieh Brachytherapy had been invented in 2012 and had a treatment in 5 days a week.

2. Materials and Methods

The study was carried out at the Mahdieh hamadan brachytherapy center and using recommendation of IAEA-47 (International Atomic Energy Agency protocol number 47) report for HDR brachytherapy units shielding [11]. First, we calculate the shielding of brachytherapy unit with the theoretical methods and formulas that have been described below.

Gamma Exposure Rate Formula

The exposure rate from a gamma point source can be approximated from the following expression

$$X = \frac{A_0 \Gamma}{r^2} \quad (1)$$

where X is the dose rate; A is activity in mCi; Γ is the gamma factor; and r distance in cm

Monoenergetic x or gamma rays collimated into a narrow beam are attenuated exponentially through a shield according to the following equation:

$$I = I_0 e^{-\mu x} \quad (2)$$

where I is the intensity outside of a shield of thickness x I_0 is the unshielded intensity μ is the linear attenuation coefficient of the shielding material x is the thickness of shielding material. The linear attenuation coefficient is the sum of the probabilities of interaction per unit path length by each of the three scattering and absorption processes—photoelectric effect, and pair production. Note that μ has dimensions of inverse length (1/cm). The reciprocal of μ is defined as the mean free path, which is the average distance the photon travels in an absorber before an interaction takes place.

Therefore, to confirm the calculations and validation of the calculation we used both experimental and Monte Carlo methods.

3. Description of the Brachytherapy Facility

The Mahdiah Radiotherapy Centre has a brachytherapy treatment rooms, a diagnostic Ct scan X-ray equipment and administrative setup. The brachytherapy treatment room shown in **Figure 1** has a concrete shield of thickness 85 cm. Flexitron machine facility at the center has a monitor located at the treatment planning room, office for monitoring the movements of the patient and communication system. **Figure 1** shows the locations around the Ir-192 sources used for the study. The specific reason for choosing this points depends on the amount of traffic in that place, work place of technicians and nurses and commonalities between the X-ray machine. In this simulation, we must simulate source in height of 1 meter from the ground and should be bare source. Locations A, B, C and F are the control area. B where the medical physicists with the Ct scan images plan the patient. Location A with a mdf and 0.4 mm lead door separates the entrance to the maze. Locations D, E are designated as the public areas and locations F is controlled area, schematic diagram to demonstrate the experiment process has been shown in **Figure 2**.

4. Monte Carlo Simulation

The brachytherapy treatment room of the Centre was modeled using the visual editor of the MCNPX code to the design specification of the facility. The concrete with a density of 2.35 g/cm^3 was used with material composition of ^1H 0.005558, ^8O 0.498076, ^{11}Na 0.017101, ^{12}Mg 0.002565, ^{13}Al 0.045746 ^{14}Si 0.315092, ^{16}S 0.001283, ^{19}K 0.019239, ^{20}Ca 0.082941, $^{26}\text{Fe}_{54}$ 0.000707, $^{26}\text{Fe}_{56}$ 0.01139 $^{26}\text{Fe}_{57}$ 0.000265, $^{26}\text{Fe}_{58}$ 3.6×10^{-5} . The entrance door of the facility is modeled as a mdf door with a density of 0.830 g/cm^3 [12]. 4 mm lead with density of

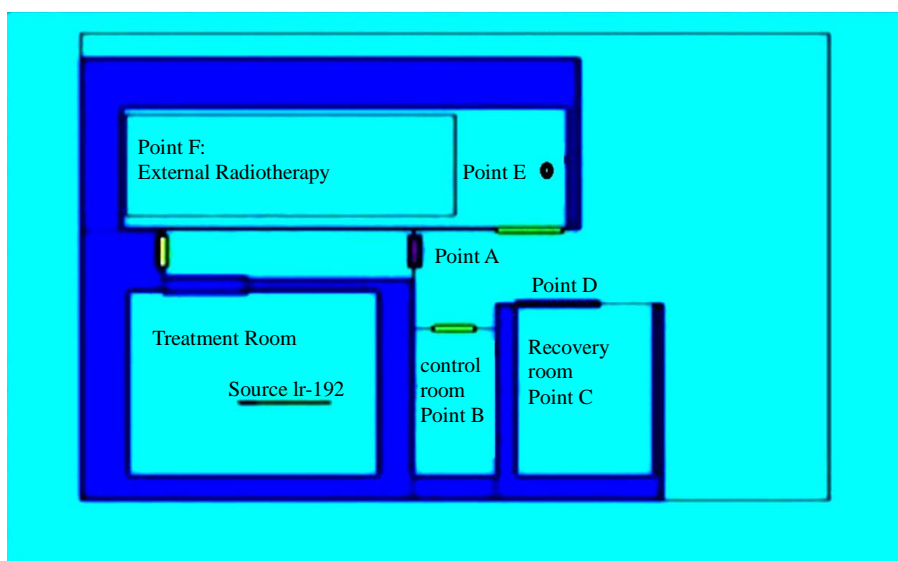


Figure 1. Brachytherapy site.

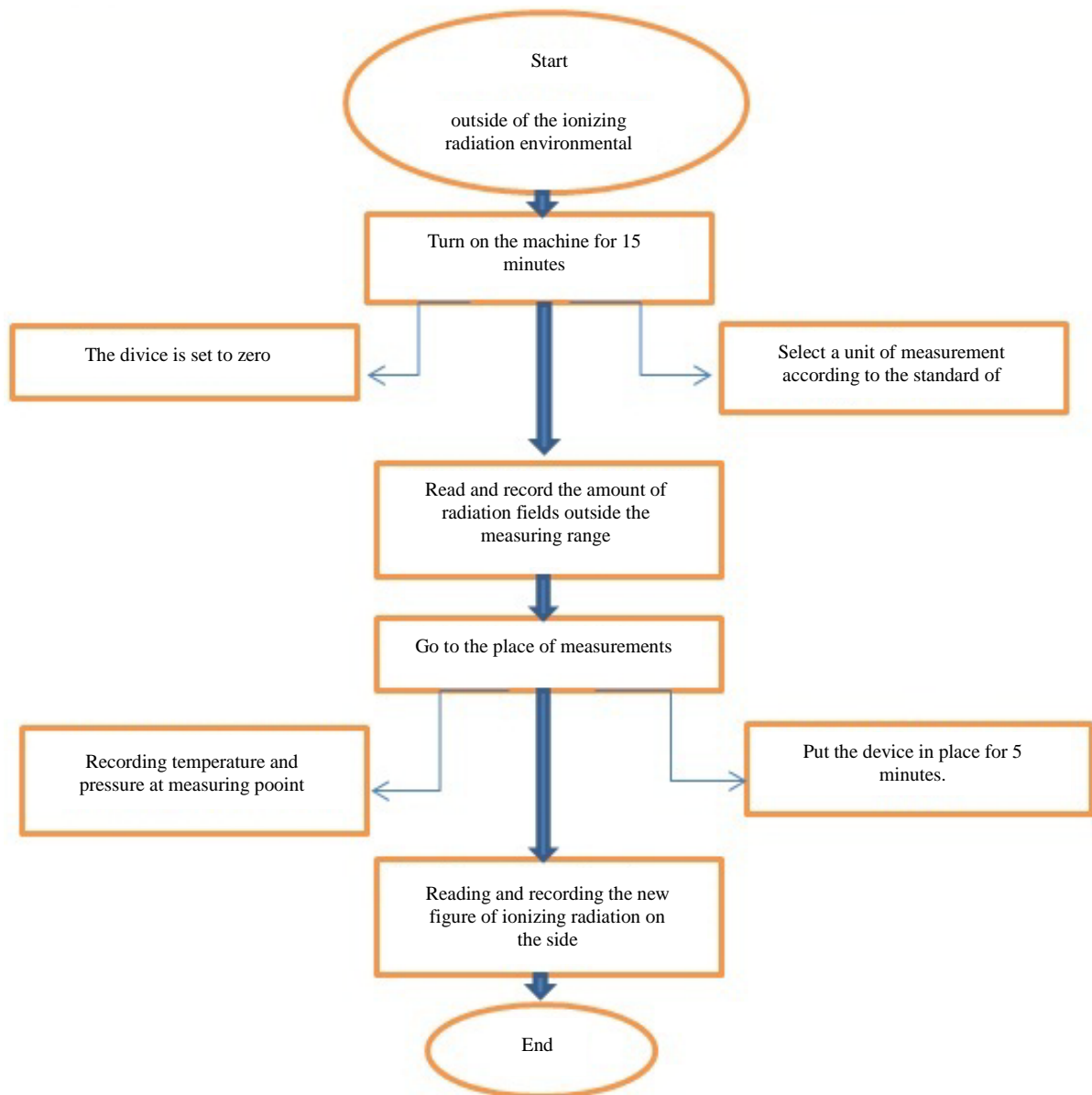


Figure 2. Schematic diagram to demonstrate the experiment process.

11.35 g/cm³ with material of ⁸²Pb₂₀₆ 0.242902, ⁸²Pb₂₀₇ 0.223827, ⁸²Pb₂₀₈ 0.53327 use in mdf door [13] [14]. Brachytherapy sources; Ir-192 was modeled as **Figure 3** with 5 activities of 11.5, 6.5, 5.7, 4.4 and 3.2 Ci.

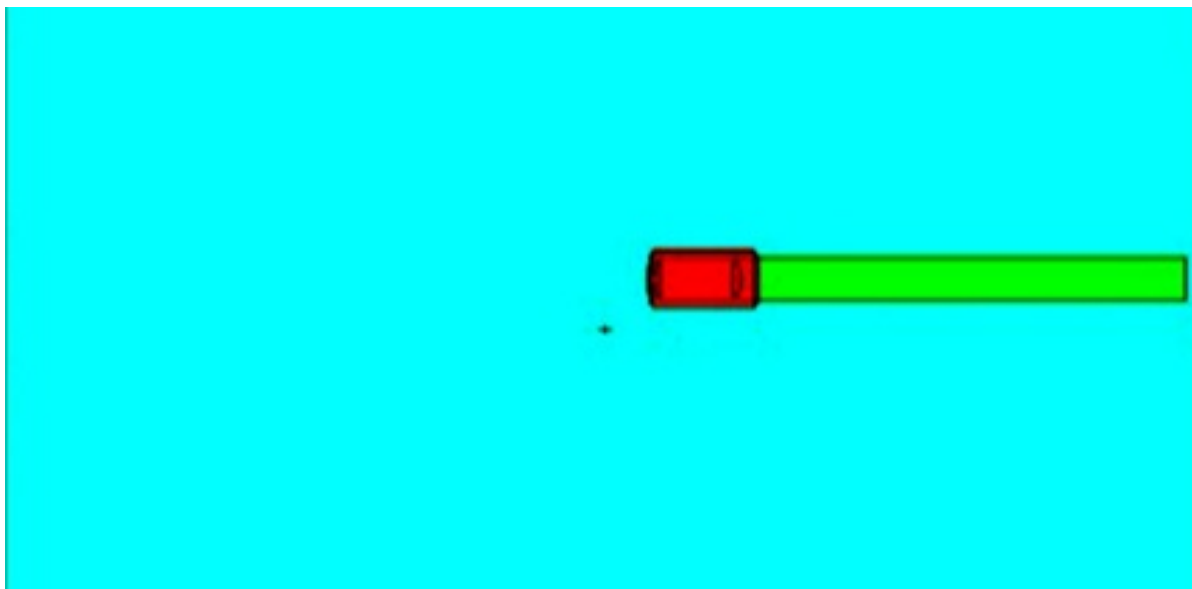
It has been in existence till date using the decay equation:

$$A = A_0 e^{-\gamma t} \quad (3)$$

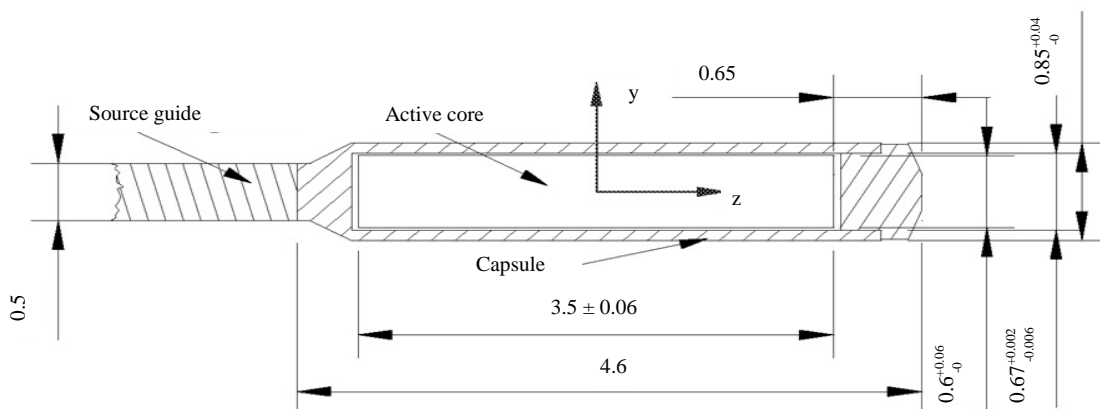
where A is the present activity, A_0 is the initial activity at a known time, γ is the decay constant and t is the time to the date of exposure. The Ir-192 HDR with activities (11.5, 6.1, 5.7, 4.4 and 3.2) Ci, was used for the modeling respectively.

Flux Tally at a Point or Ring (Type F5)

This type of tally makes use of what some might call a variance reduction technique, namely, use of the “next event estimator.” For each source particle and each collision event, a deterministic estimate is made of the fluence contribution at the detector point (or ring in an axisymmetric problem). To simplify description of this type



The braided stainless-steel cable was assumed to be 5-mm long and to consist of solid stainless-steel.



The coordinate system is located at the center of the active part of the source
Dimensions are in mm

Figure 3. Schematic design and geometry of brachytherapy flexitron Ir-192 source.

of tally, assume that calculations are being performed in a uniform medium. Suppose a particle of energy E and weight W from an isotropic source is released at distance r from the detector point. Ray theory methodology, as used in the point-kernel method, dictates that the contribution $\delta\Phi$ to the fluence at the detector point is given by:

$$\delta\Phi = \frac{W}{4\pi r^2} e^{-\mu E r} \quad (4)$$

in which $\mu(E)$ is the linear interaction coefficient for the particle of energy E . Note that $1/4\pi$ per steradian is the angular distribution of a point isotropic source. Now suppose that a collision takes place at distance r from the detector point and that, to reach the detector point, a scattering angle of θ_s would be required. Here, E is the energy of the particle after the collision and W is its weight. If $\mu(E, \theta_s)$ is the linear interaction coefficient per steradian for scattering at angle θ_s , then $\mu(E, \theta_s)/\mu(E)$ is the probability per steradian for scattering at angle θ_s . Geometric attenuation remains as $1/r^2$, and the contribution $\delta\Phi$ to the fluence at the detector point is given by

$$\delta\Phi = \frac{W\mu(E, \theta_s)}{\mu(E)r^2} e^{-\mu E r} \quad (5)$$

5. Dose Rate Measurement

Locations where dose rate had been estimated in thereby using MCNP5 were first identified and then measured the corresponding distances from the source. Dose rate monitoring was carried out for the selected locations A, B, C, D, E, and F in meter. Measuring doses must be in the range of 0.5 $\mu\text{Sv/h}$ - 7.5 $\mu\text{Sv/h}$. for experimental measurement we used the STEP RDG Detector with Measuring range of 0 - 2000 $\mu\text{Sv/h}$ and 1.06 correction factor that shown in **Figure 4**.

6. Results and Discussion

Result in **Tables 1-5** and **Figures 5-9** shows experimental measurement for a Ir-192 HDR source with apparent activity. All of measurement dose rate are under the reference dose rate recommendation of International Atomic Energy Agency.



Figure 4. Schematic view of STEP RDG detector.

Table 1. Measurement and comparison between experimental dose rate, referenced dose rate and simulated data for source with 11.5 Ci activity.

Location	Table column head				
	Distance from source (m)	Measured dose rate ($\mu\text{Sv/h}$)	Reference dose rate ($\mu\text{Sv/h}$)	Activity (Ci)	Simulated dose Rate ($\mu\text{Sv/h}$)
Point A	1.5	0.71	7.5	11.5	0.94
Point B	2	0.68	7.5	11.5	0.33
Point C	3	0.66	7.5	11.5	0.166
Point D	3.5	0.5	0.5	11.5	0.32
Point E	4	0.45	0.5	11.5	0.16
Point F	5	0.45	7.5	11.5	0.89
STD	-	0.121119775	-	-	0.354367982
avg	-	0.575	-	-	0.467666667
St.Dev.%	-	0.210643088	-	-	0.757736241

Table 2. Measurement and comparison between experimental dose rate, reference dose rate and simulation data for source with 6.1 Ci activity.

Table column head					
Location	Distance from source (m)	Measured dose rate ($\mu\text{Sv/h}$)	Reference dose rate ($\mu\text{Sv/h}$)	Activity (Ci)	Simulated dose Rate ($\mu\text{Sv/h}$)
Point A	1.5	0.68	7.5	6.1	0.85
Point B	2	0.66	7.5	6.1	0.33
Point C	3	0.66	7.5	6.1	0.11
Point D	3.5	0.48	0.5	6.1	0.28
Point E	4	0.45	0.5	6.1	0.15
Point F	5	0.45	7.5	6.1	0.668
STD	-	0.113959057	-	-	0.296715352
avg	-	0.563333333	-	-	0.398
St.Dev.%	-	0.202294184	-	-	0.745515959

Table 3. Measurement and comparison between experimental dose rate, reference dose rate and simulation data for source with 5.7 Ci activity.

Table column head					
Location	Distance from source (m)	Measured dose rate ($\mu\text{Sv/h}$)	Reference dose rate ($\mu\text{Sv/h}$)	Activity (Ci)	Simulated dose Rate ($\mu\text{Sv/h}$)
Point A	1.5	0.54	7.5	5.7	0.82
Point B	2	0.54	7.5	5.7	0.32
Point C	3	0.51	7.5	5.7	0.105
Point D	3.5	0.45	0.5	5.7	0.28
Point E	4	0.45	0.5	5.7	0.15
Point F	5	0.45	7.5	5.7	0.66
STD	-	0.045166359	-	-	0.287618092
avg	-	0.49	-	-	0.389166667
St.Dev.%	-	0.092176243	-	-	0.739061478

Table 4. Measurement and comparison between experimental dose rate, reference dose rate and simulation data for source with 4.4 Ci activity.

Table column head					
Location	Distance from source (m)	Measured dose rate ($\mu\text{Sv/h}$)	Reference dose rate ($\mu\text{Sv/h}$)	Activity (Ci)	Simulated dose rate ($\mu\text{Sv/h}$)
Point A	1.5	0.61	7.5	4.4	0.802
Point B	2	0.64	7.5	4.4	0.32
Point C	3	0.43	7.5	4.4	0.1
Point D	3.5	0.44	0.5	4.4	0.27
Point E	4	0.42	0.5	4.4	0.15
Point F	5	0.49	7.5	4.4	0.61
STD	-	0.096488341	-	-	0.274901194
avg	-	0.505	-	-	0.375333333
St.Dev.%	-	0.191066022	-	-	0.732418813

Table 5. Measurement and comparison between experimental dose rate, reference dose rate and simulation data for source with 3.2 Ci activity.

Location	Table column head				
	Distance from source (m)	Measured dose rate ($\mu\text{Sv/h}$)	Reference dose rate ($\mu\text{Sv/h}$)	Activity (Ci)	Simulated dose rate ($\mu\text{Sv/h}$)
Point A	1.5	0.68	7.5	3.2	0.79
Point B	2	0.66	7.5	3.2	0.3
Point C	3	0.66	7.5	3.2	0.097
Point D	3.5	0.51	0.5	3.2	0.267
Point E	4	0.45	0.5	3.2	0.12
Point F	5	0.45	7.5	3.2	0.58
STD	-	0.110166541	-	-	0.272877995
avg	-	0.568333333	-	-	0.359
St.Dev.%	-	0.19384142	-	-	0.760105835

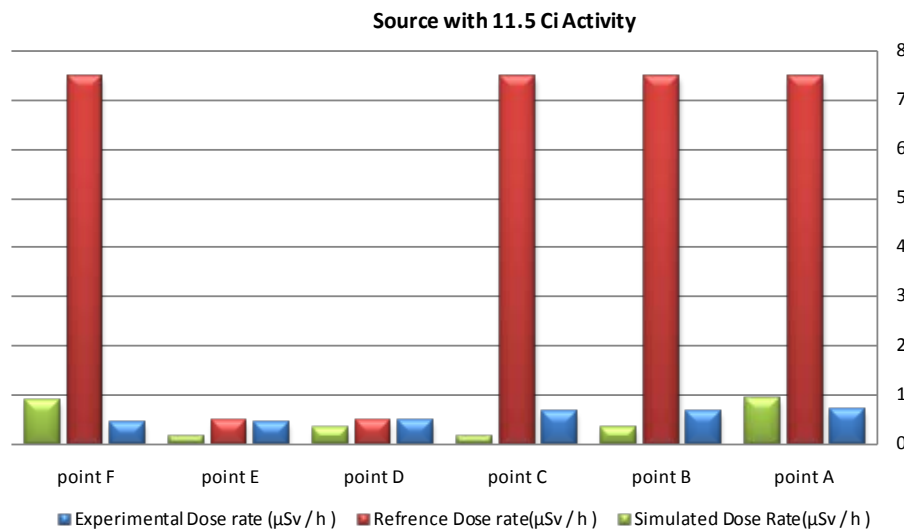


Figure 5. Schematic view of measured dose rate, reference dose rate and simulated dose rate for each point for the source with 11.5 Ci activity.

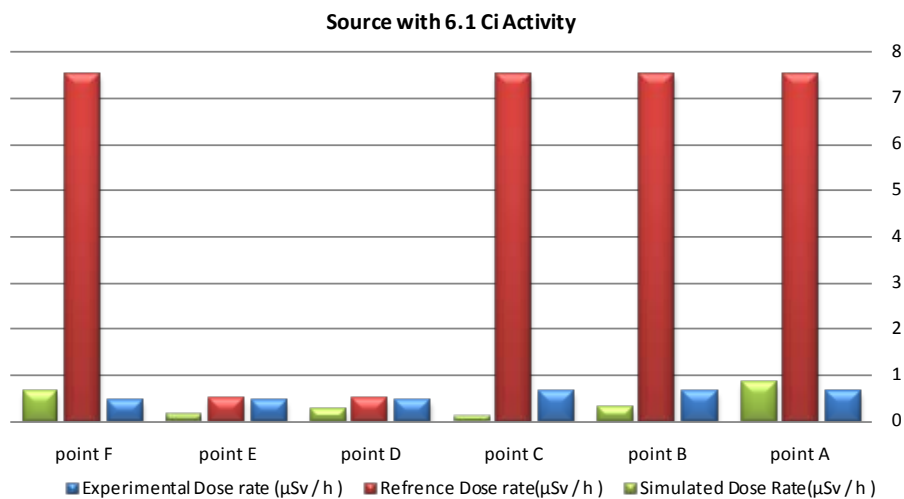


Figure 6. Schematic view of measured dose rate, reference dose rate and simulated dose rate for each point for the source with 6.1 Ci activity.

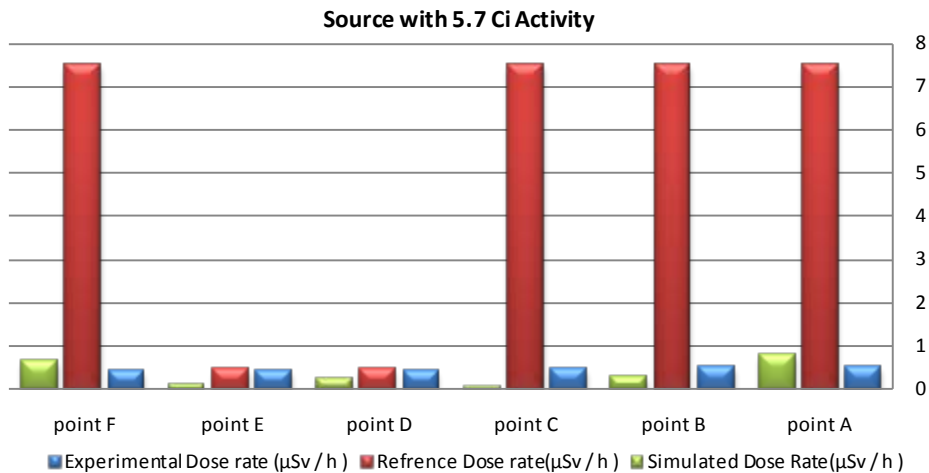


Figure 7. Schematic view of measured dose rate, reference dose rate and simulated dose rate for each point for the source with 5.7 Ci activity.

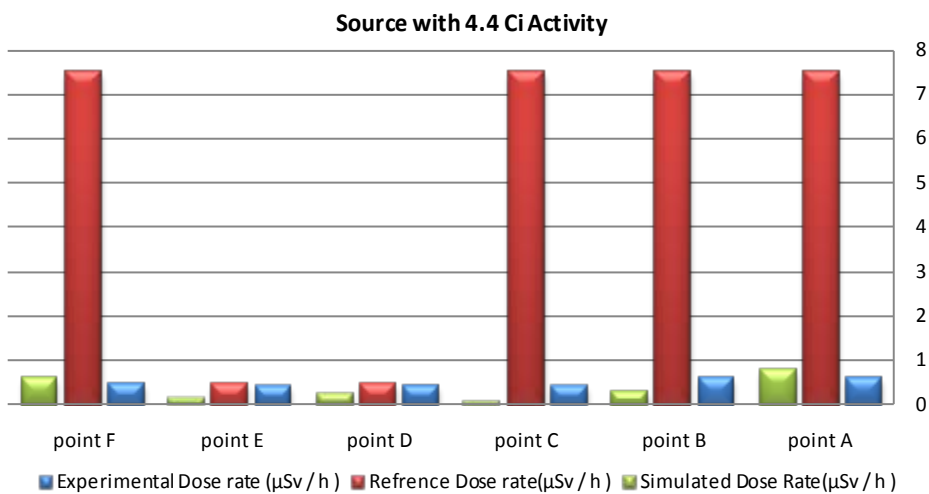


Figure 8. Schematic view of measured dose rate, reference dose rate and simulated dose rate for each point for the source with 4.4 Ci activity.

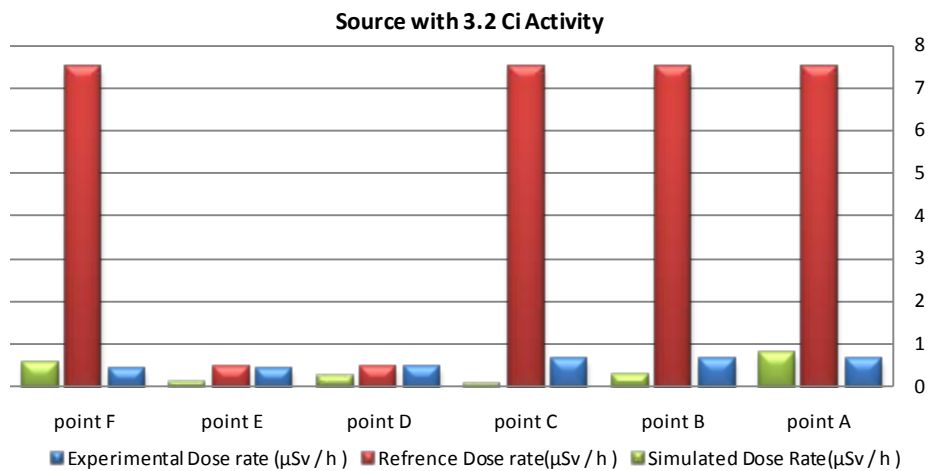


Figure 9. Schematic view of measured dose rate, reference dose rate and simulated dose rate for each point for the source with 3.2 Ci activity.

7. Conclusion

The measured dose rates at the selected locations representing supervised areas are all below the recommended values for public areas of 0.5 $\mu\text{Sv/h}$. The controlled areas are also below the value recommended for controlled areas of 7.5 $\mu\text{Sv/h}$. This implies that the biological shielding design of the facility is adequate to attenuate the gamma radiations from the brachytherapy sources used for treatment and hence the general public and staff are adequately protected for the existing HDR Ir-192 brachytherapy system. But unfortunately we saw an over estimate in calculation of room shielding design.

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