https://doi.org/10.5392/IJoC.2018.14.4.065

Simple Calculation Method as a Supplementary Radiation Safety Assessment for Facility with Radiation Generator

Sang-Tae Kim
Nuclear Emergency Division, Nuclear Safety and Security Commission, Seoul, Korea

ABSTRACT

The objective of this study was to conduct a radiation shielding analysis for the facility equipped with radiation generator. The analysis was carried out in two aspects. First, from the aspect of the effect caused by primary and leakage radiation. Second, effect of scattered radiation was evaluated by applying a simple calculation method based on a scattering rate concept since effect of scattered radiation is significantly important at maze entrance of the radiation facility. The calculated results obtained using the simple method were compared to the results calculated using Geant4 code and the measured values. The results calculated by the suggested method indicate that slight error exists in a radiation shielding analysis done at the maze entrance comparing to other two results, while the results evaluated at the outside of the maze entrance door are relatively consistent with other values.

Key words*: Radiation Generator, Shielding Analysis, Primary Radiation, Leakage Radiation, Scattered Radiation.*

1. INTRODUCTION

In facilities where radioisotope and radiation generator are being used, radiation will be leaked to outside of facility. As a result, radiation workers who handle radiation sources directly or indirectly as well as workers who do not directly handle it in the facility would be affected by the radiation no matter how much dose is. To relieve this problem, the countries around the world enact and enforce the law in which dose limit for radiation is set so as to protect people from exposure to radiation. In South Korea, the Nuclear Safety Act was enacted to set the permitted dose limit. The Nuclear Safety Act regulates that dose limit for a radiation worker is not allowed to exceed 50mSv per year and 100mSv per 5 years, dose limit for a person with frequent access or a person who delivers radioactive materials is not allowed to exceed 6mSv per year, and dose limit for a general person is not allowed to exceed 1mSv [1]. Currently, radiation protection related things such as dose limit are required to comply with ICRP 60. A compliance with ICRP 103 in a situation of domestic radiation use are under a deliberate consideration.

To reduce unnecessary radiation exposure from the use of it, it is necessary to make effort to minimize leakage radiation from radiation facility as little as possible and minimize radiation exposure to people. The X-ray released by a radiation generator has identical characteristics of the gamma-ray. For the gamma-ray emitted by radioisotope, its energy distribution can be inferred. In contrast, it is hard to accurately measure the energy distribution for the X-ray emitted by a radiation generator. In designing radiation shielding for the facility with radiation generator, thus, an experimental analysis methodology described in NCRP 49, 51 and 151 is mostly being used rather than theoretical analysis methodology that is used in gamma-ray facility [2]-[4].

In this study, an experimental analysis method for primary and leakage radiation was briefly introduced first. For an analysis on scattered radiation, a computer code using Monte-Carlo technique can produce comparably good results. However, this study aimed at proposing more simplified and faster method which is still capable of getting the desired calculation results. To achieve this, this study developed a model based on a concept of scattering rate. This method was verified by comparing the value calculated using the simple calculation method to the value obtained via Monte-Carlo based computer code Geant4 (Geometry and Tracking 4) [5] and the on-site measured value.

2. MATERIALS AND METHODS

Primary radiation, also called as direct radiation is a direct exposure to X-ray which is emitted by radiation generator. Analysis method for this is described in NCRP report in details. It can be expressed as the following equation [2]-[4].

$$B_x = \frac{P(d_{pri})^2}{WUT} \quad (1)$$

P : dose limit
d_{pri} : focus to object distance(m)
W : Workload
U : Use Factor
T : Occupancy factor

* *Corresponding author, Email: st.kim7@daum.net*
Manuscript received May. 15, 2018; revised Dec. 21, 2018; accepted Dec. 21, 2018

To determine the thickness of shielding material, B_x needs to be calculated using the Eq. (1). With this value, then refer to the attenuation table in NCRP 49, 51 and 151 which provides comparison between radiation generator and shielding material [2]-[4].

The dose limit of leakage from radiation generator is generally specified in a design requirement for a generator. It is regulated to be less than 0.1% of the available beam exposure at 1 m from the radiation source [2]. Therefore, the shielding for leakage radiation compared to primary radiation would be ignorable.

$$B_L = \frac{1000P(d_{pri})^2}{WT} \quad (2)$$

The equation to calculate transmission factor for leakage radiation can be expressed as the Eq. (2) even though it may vary depending on output power of radiation generator.

Likewise, the thickness of shielding material for leakage radiation can also be obtained using BL which is calculated by the Eq. (2). With this value, refer to the attenuation table specified in NCRP and get the corresponding value [2]-[4]. Shielding analysis for primary and leakage radiation procedure and its result were omitted from this paper because they are quite straightforward as explained above.

In evaluating the scattering of X-ray emitted by high-energy radiation generator facility, the traditional calculation method already exists but it is generally not used because the calculation procedure is lengthy and complex due to the complicated geometric structure of the facility and the scattering effects caused by various media. Instead of this method, Monte-Carlo simulation which was developed for the same purpose is being frequently used to get comparably accurate analysis results in conjunction with a computer code. However, disadvantage definitely exists even in using the computer code. An effective use of computer code requires an expensive computer system with high performance. Additionally, considerable amount of time and efforts are required to be spent implementing codes which can cover the highly diversified and complicated irradiation situation, and reducing the number of errors even after completion of coding.

Primary and secondary transmission effects on shielding wall for the scattered radiation occurring at inside of facility will not be a big problem since the amount of radiation energy would be weaker than that of primary radiation energy because it already is attenuated through several scattering happening. Only problem in this situation would be the scattered radiation occurring at curved entrance of the facility. This study adopted a concept of scattering rate in evaluating dose of scattered radiation at maze entrance to derive simple calculation method. The results obtained by using this simple calculation method were verified by comparing the calculated value using Geant4 code and the on-site measured value.

2.1 Scattering Rate of Photons

Generally, a scattering rate is defined as a ratio of the incident current and the reflected current on a surface. It can be expressed as the Eq. (3)

$$J(E,\theta,\Phi) = J(E_0,\theta_0) \cdot \alpha_0(E_0,\theta_0,E,\theta,\Phi) \quad (3)$$

$J(E, \theta, \Phi)$: Reflected current
$J(E_0, \theta_0)$: Incident current
$\alpha_0(E_0, \theta_0, E, \theta, \Phi)$: Differential dose scattering rate
E_0 : Incident radiation energy
θ_0 : polar angle
E : Reflected radiation energy

In Fig. 1, the dose rate of the irradiated object affected by the radiation reflected from microarea dA can be written as the Eq. (4).

$$dD = \frac{D_0 \cdot cos\theta_0 \cdot dA \cdot \alpha_0}{r^2} \quad (4)$$

D_0 : Incident radiation from microarea dA

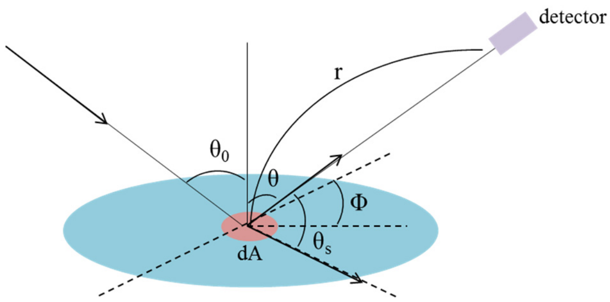


Fig. 1. Measurement of radiation reflected from microarea dA

Other reaction which contributes to the reflected energy at a surface is caused by a pair production that occurs at photon energy of 1.02MeV and above. Two photons are created. This phenomenon more frequently happens at higher incident radiation energy than 5MeV.

Photon energy generated by a pair production will be higher than scattering energy at a scattering angle of 90 degree or larger in Compton scattering (Eq. 5). Therefore, the effect of a pair production will contribute to larger portion of the scattering rate value in a condition where the incident photon energy is greater than 5MeV and the scattering angle is larger than 90 degree.

$$E = \frac{E_0}{1+\left(\frac{E_0}{0.511}\right)(1-cos\theta_s)} \quad (5)$$

E_0 : Incident radiation energy
E : Reflected radiation energy
θ_s : scattering angle

2.2 Evaluation and Measurement of Radiation Dose at Facility Entrance

The experiment was carried out at the facility in which 6MV energy linear accelerator was being installed and used. It is commonly used medical equipment in radiosurgical treatment. The Fig. 2 shows the structure of the facility. Since an evaluation of the effects for all scattered radiations adjacent to entrance by means of the simple calculation method is practically not feasible, the evaluation was carried out under the assumptions as follows.

1) The position where dose rate evaluation is performed is the center of entrance at 1 m distance from the floor.
2) The locations primarily seen from the evaluation position are selected as the scattering position.
3) Radiation streaming through the gap of ceiling, floor and entrance is ignored.
4) The X-ray energy arriving at entrance is assumed to 0.511MeV.
5) The radiation dose intensity is assumed to 3Gy/min for an area of 100cm^2 at 1 m distance
6) The X-ray energy emitted by a radiation generator is assumed to 6MV.
7) The scattering effect caused by other equipment rather than concrete structure in the facility is ignored.
8) Leakage radiation dose from a radiation generator is assumed to 0.1% of dose due to available beam which is specified by a design requirement.

Table 1. Constant by Materials and Energies

Material	E_0(MeV)	Constant
Concrete	0.2	0.0023
	0.662	0.0347
	1.00	0.0503
	2.50	0.0999
	6.13	0.1717

The scattering rate used in the simple calculation can be expressed as the Eq. (6) which represents a scattering rate of differential dose for concrete [6]-[7].

$$\alpha_d = \frac{C \cdot K(\theta_s)\times 10^{26} + C\prime}{1+\left(\frac{\cos\theta_0}{\cos\theta}\right)} \quad (6)$$

Here, denotes a constant by materials and energies as shown in Tab. 1.

$$K(\theta_s) = \frac{R_S^2}{2}\left(P^2 + P^3 \cdot \sin^2\theta_s + P^4\right) \quad (7)$$

$$R_s = 2.818 \times 10^{-13} cm$$

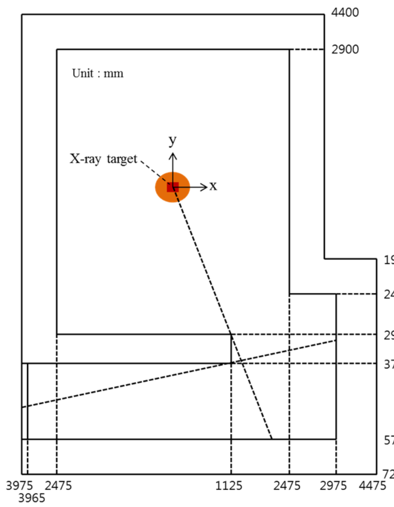
$$P = \frac{1}{1+\left(\frac{E_0}{0.511}\right)(1-\cos\theta)}$$

D_0 : Incident radiation dose in reflective plane
α_{Di} : Scattering rate in reflective plane
S_{Ai} : Reflective area
$\cos\theta_k$ Cosine of reflective area
$e^{-\mu t}$: Attenuation effect at the door
ri : Source to reflective plane distance
rj : Reflective plane to measurement point distance

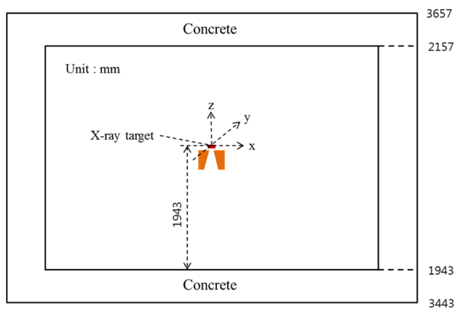
In this study, the Monte-Carlo based computer code, Geant4 was used to calculate dose rate of the X-ray transmitting shielding wall. Geant4 is a computer code implemented in C++ language. It enables a computer simulation on microscopic interaction occurring between particles and materials. It is being widely used in various areas ranging from high energy physics, medical physics to astrophysics. It also is equipped with a variety of physics models that can be applied to researchers' studies on interaction between particles such as photon, electron and hadron. In particular, Geant4 provides three different types of models on electromagnetic interaction: standard, low-energy and Penelope model. In this study, low-energy model was used. The applicable energy ranges from 250 eV to 100GeV in this model. In addition to this, Geant4 allows for consideration of photoelectric effect, Compton scattering, Rayleigh scattering, bremsstrahlung, ionization and luminescence of exited atom [4], [5]. The version of Geant4 used in this study is 9.5.p01. For calculation purpose, the X-ray was assumed to a point source. Then 5×10^8 particle histories were applied. Evaluation with use of Geant4 and on-site measurement were carried out 10 times each except for simple calculation method.

Two different types of shielding materials were used: concrete for a shielding wall and lead for radiation generator and entrance. Geometric structure of the facility is presented in the Fig. 2. The scattering model is depicted in the Fig. 3.

The measurement for dose rate was conducted at inside and outside of entrance using a radiation detector, which is the calibrated GM counter (Model: FH40 F4, Thermo Eberline ESM, Germany) accredited by the Korean Laboratory Accreditation Scheme (KOLAS) accepted by "International Laboratory Accreditation Cooperation" through mutual recognition agreement.



(a) Ground plan



(b) Side view

Fig. 2. Geometric structure for the inside of facility utilizing radiation generator (linear accelerator)

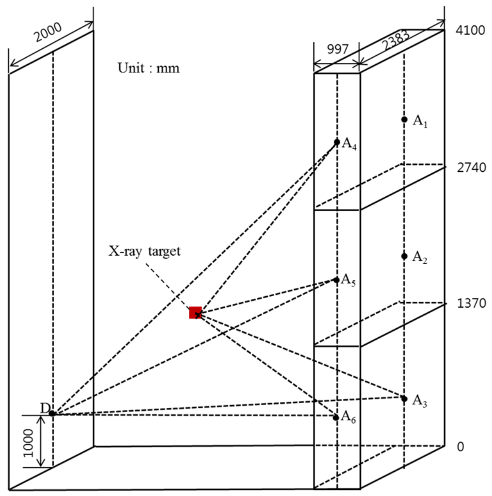


Fig. 3. Scattering model for the inside of facility utilizing radiation generator (linear accelerator)

These radiations with very low energy could make significant effect on the values obtained by measurement and computer code calculation, while these radiations could not make much effect at outside because they get attenuated while passing through the door in locations at the outside of entrance such as a control room and a passage way where the radiation workers are mostly staying and working..

Table 2. Compare three values obtained using two different calculation techniques and measurement for the facility with medical radiation generator (linear accelerator) ($p<0.05$)

<mSv/h>

	Geant4 code calculation	**Simple calculation**	**Measurement**
Inside door	1.11±0.07	0.53	1.66±0.05
Outside door	0.11±0.02	0.09	0.15±0.03

3. RESULTS AND DISCUSSIONS

To verify the effectiveness of the proposed simple calculation method, dose rate at entrance was evaluated or measured in three ways: (a) using the simple calculation method, (b) using the computer code, and (c) using the radiation detector. In calculating by means of the computer code, the directly transmitted radiation and contribution by all the scattered radiation which were not considered in simple calculation, were taken into account. The calculation results and measurement results are listed in the Table 2. The Table 2 indicates that the relative standard deviation (RSD) in calculation by computer code is relatively higher than others. The reason might be because photons having very small energy contribute to detection point due to multiple scattering. The results also indicate that there is little difference in the measured value and the calculated value using simple calculation method, but there is significantly considerable difference in these two values and computer-code calculated value. The reason of this might be because the thickness of lead was arbitrarily set due to no prior information on detailed mechanical specification for the radiation generator.

Dose rate for the inside of entrance indicates considerable difference in three values (on-site measurement, simple calculation method and computer code calculation method), which might be because simple calculation method considers only primary scattering effect by leakage radiation dose, while the other two methods consider all the possibly contributable effects by transmission radiation and multiple scattering.

As expected from the calculation results using a computer code, particularly, dose rate at entrance is affected largely by leakage radiation rather than by scattered radiation from available beam. Dose rate at the mainly interested position which is the outside of entrance shows not much difference in three methods. In contrast, dose rate at the inside of entrance shows considerable difference in three different methods. This can be explained that lots of radiations with very low energy due to multiple scattering mainly exist at the inside of entrance.

4. CONCLUSION

In this study, the effect by scattered radiation at entrance of the facility equipped with a radio-therapeutic linear accelerator was evaluated by comparing the dose rates obtained by three different methods: Monte-Carlo based computer code calculation method, simple calculation method and on-site measurement using a radiation detector. Although it is true that the use of a computer code is the best approach, the simple calculation technique proposed in this study can be the second best solution if an alternative approach is necessary depending on the situation. The simple calculation method allows the user to significantly save the amount of resources that might be required for running a computer code. Even this method can be used in a situation where computer is not available. This method can produce comparably good result with only small amount of resources.

To test the validity of the results that came out using the simple calculation, experiment was carried out at the facility where cancer therapeutic linear accelerator was being used. In this experiment, the values obtained by computer code calculation and measurement were compared to the value calculated by the simple method. The test results indicate that the simple calculation method proved to be applicable to the facility with relatively complex structure. Therefore, this simple calculation method can be expected to be applicable to the shielding design and safety assessment for the facilities with similar structure to this as well as with simpler structure without sacrificing the quality of the evaluation results.

REFERENCES

[1] Enforcement Decree of the Nuclear Safety Act, Prom No 27972, NSSC, 2017.

[2] NCRP Report No. 49, *Structural shielding design and evaluation for medical use of X-rays and gamma rays of energies up to 10 MeV*, NCRP, Bethesda, 1976.

[3] NCRP Report No. 51, *Radiation protection design guidelines for 0.1-100 MeV particle accelerator facilities*, NCRP, Washington DC, 1977.
[4] NCRP Report No. 151, *Structural shielding design and evaluation for megavoltage X- and gamma-ray radiotherapy facilities*, NCRP, Bethesda, 2005.
[5] GEANT4 Collaboration, *Geant4 User's Documents, Introduction to Geant4 for GEANT4,* CERN, 2007.
[6] GEANT4 Collaboration, *Physics Reference Manual Version: Geant4 9.5.0 for GEANT4,* CERN, 2011.
[7] A. B. Chilton and J. K. Shultis, and R. E. Faw, *Principles of Radiation Shielding*, Prentice-Hall, Inc., Englewoos Cliffs, 1984.
[8] J. E. Martin, *Physics for Radiation Protection*, Wiley, WeinHeim, 2013.

Sang-Tae Kim
He is a government official who is working for Nuclear Safety and Security Commission, Korea. He received the Ph.D. in radiation science and technology from Chonbuk National University, Korea in February 2012. His main research interests include radiation protection and health/medical physics.