Monte Carlo MCNP-based simulation and radiation measurement of Yttrium-90 bremsstrahlung produced from radiation shielding apparatus

C Onnomdee¹, C Jumpee², J Channuié³, P Sinkaew³, K Chuamsaamarkkee¹,⁴, P Charoenphun¹,⁴

¹Master of Science Program in Medical Physics, Faculty of Medicine, Ramathibodi Hospital, Mahidol University, Bangkok, 10400, Thailand
²Faculty of Associated Medical Sciences, Chiang Mai University, Chiang Mai, 50200, Thailand
³Thailand Institute of Nuclear Technology, (Public Organization), Nakhonnayok, 26120, Thailand
⁴Department of Therapeutic and Diagnostic Radiology, Faculty of Medicine, Ramathibodi Hospital, Mahidol University, Bangkok, 10400, Thailand

E-mail: ps4436@hotmail.com

Abstract. Yttrium-90 (⁹⁰Y) has been widely used in therapeutic nuclear medicine including in the selective internal radiation therapy with ⁹⁰Y-microsphere. In the procedure ⁹⁰Y source is protected within the radiation shielding apparatus made of perspex. However, bremsstrahlung radiation may be generated when ⁹⁰Y interacts with matter. The aim of this study was to evaluate bremsstrahlung radiation produced from radiation shielding apparatus using a scintillation detector and Monte Carlo simulation. The ⁹⁰Y source in glass vial was placed in the radiation shielding apparatus. Bremsstrahlung measurement and spectrum were performed and recorded using thallium-doped sodium iodide (NaI(Tl)) scintillation detector. Counting time and distance between the detector and apparatus were varied to obtain the optimal condition for bremsstrahlung measurement. Monte Carlo N-Particle (MCNP) 5 was used to simulate bremsstrahlung radiation with the same geometry used in the measurement. For experimental measurement results, the optimal distance and counting time were 10 cm and 120 s, respectively. Although the result of bremsstrahlung spectrum from the detector and simulation exhibited similar trend, markedly greater count rate was observed in simulations than in detector measurements. In conclusion, ⁹⁰Y bremsstrahlung can be produced from radiation protection apparatus and this can be evaluated by either measurement or simulation.

1. Introduction
Plastic or low atomic number materials such as perspex are suitable to be used as radiation shielding for beta emitter radionuclides [1]. A radiation shielding apparatus made of perspex is used to store ⁹⁰Y microsphere vials during the process of selective internal radiation therapy (SIRT). The interaction of beta particles emitted from ⁹⁰Y decay with atomic nuclei of the perspex produces bremsstrahlung radiation. Based on this phenomenon, bremsstrahlung radiation may be produced from radiation
shielding apparatus while performing treatment with $^{90}$Y microspheres and this might lead to increase of radiation exposure to related staff.

Bremsstrahlung radiation can be measured with radiation detectors such as ionisation detector and scintillation detector. Researchers demonstrated that scintillation detectors were able to measure bremsstrahlung and bremsstrahlung spectrum could be obtained when a multichannel analyser was connected to the detector [2, 3]. Not only radiation detectors are able to determine bremsstrahlung radiation: Monte Carlo simulation has also been used to study bremsstrahlung radiation [4]. In addition, the results of Monte Carlo simulations were compared with those of measurements. Therefore the aim of this study was to evaluate bremsstrahlung radiation produced from radiation shielding apparatus using scintillation detector and Monte Carlo simulation.

2. Materials and methods
Experiments were mainly separated into two parts, measurement of bremsstrahlung radiation with NaI(Tl) scintillation detector and simulation with MCNP transport code.

2.1. Experimental measurement
In these experiments, scintillation detector was used to measure bremsstrahlung radiation of $^{90}$Y after $^{90}$Y interacts with radiation shielding apparatus described as follows.

Prior to performing the experiments a 2"x2" NaI(Tl) scintillation detector (Mirion Technologies, Inc., California, the United States of America) was pre-calibrated by standard sources as follows. The Americium-241 ($^{241}$Am, 59.54 keV), Caesium-137 ($^{137}$Cs, 661.66 keV), and Cobalt-60 ($^{60}$Co, 1173.24, 1332.50 keV) standard sources were chosen as they represent low, medium and high energy. First, the NaI(Tl) scintillation detector was set up with lead shielding blocks (Figure 1). Background radiation was measured for 5 minutes. Calibration sources were then placed at 10 cm from the detector window as shown in Figure 1 and the count rate was recorded for 5 minutes before recording the energy spectrum to obtain full-width at half maximum (FWHM) in order to calculate energy resolution [5, 6].

In the next set of experiments we sought to determine the optimal distance and time which can be used to reliably measure produced bremsstrahlung radiation. Four surfaces of the apparatus were labelled as shown in Figure 2. Yttrium trichloride ($^{90}$YCl$_3$) with activity around 800 μCi in 4 mL was prepared in a glass vial which was then placed in a perspex vial shielding before storing in the radiation shielding apparatus as outlined in Figure 2. The measurement was performed as follows. Prior to measuring bremsstrahlung radiation, the background radiation was counted for 5 minutes. The apparatus with $^{90}$Y source was then placed in front of the scintillation detector window at varied distances of 0.5, 5 and 10 cm (Figure 2). At each distance, a measurement was performed for 30, 60 and 120 seconds. Radiation count rates were measured alongside all surfaces in order to take into account the different configurations inside the radiation shielding apparatus. Statistical analysis was performed using Two-
way ANOVA statistic to test the differences of the measurement among different surfaces. Optimal
distance was defined as the distance with the lowest (and below 10%) detector dead time [2, 3] and the
optimal counting time was defined as the one with the lowest standard deviation of the count rate [6].
Once optimal conditions have been determined count rate against energy was plotted to obtain the
gamma spectrum.

2.2. Simulation with MCNP
The MCNP code using the F8 tally was used in the study. The simulation of the radiation measurement
system was modelled similar to the experimental conditions (Figure 3 and 4) including geometry,
dimensions and material densities by MCNP5 transport code. The MCNP simulation procedure was
primarily validated by a $^{137}$Cs gamma point source as it is generally used for NaI(Tl) detector calibration
[7]. The Gaussian Energy Broadening (GEB) card was additionally applied. A deviation of less than 2%
from the experimental measurement was required prior to utilising this code to simulate the produced
bremsstrahlung radiation [8, 9].

3. Results

3.1. Experimental measurement
The initial calibration of the NaI(Tl) scintillation detector with the $^{241}$Am, $^{137}$Cs, and $^{60}$Co sources
showed good energy calibration corresponding to the respective gamma energies as expected. The
energy resolution of $^{241}$Am (59.54 keV) and $^{137}$Cs (661.66 keV) was 19.67% and 8.03%, respectively,
and energy resolution of $^{60}$Co (1173.24 and 1332.50 keV) source was 5.28% and 4.86%.

The distance between the detector and radiation shielding apparatus containing a $^{90}$Y source and the
counting time were varied. Measurements of $^{90}$Y bremsstrahlung radiation were recorded alongside all
surfaces of the radiation shielding apparatus. Radiation count rates were not significantly different
alongside the surfaces of the radiation shielding apparatus (p-value < 0.01). In the clinical practice of
SIRT with $^{90}$Y microsphere, surface 3 (S3) (Figure 2) of the radiation shielding apparatus is the operator
facing side therefore the radiation count rates from this surface were selected to determine the optimal
distance and time. Table 1 and 2 show the summary of dead times and standard deviations of the counts
at various distances and times. The distance of 10 cm and counting time of 120 seconds was found to
be the optimal experimental setup because of the lowest detector dead time and lowest standard
deviation of the count rate, 1.72% and 0.20, respectively.
### Table 1. Dead time of counting system when varied the distances (n=3).

| Distance (cm) | Dead time (%) |
|---------------|---------------|
| 0.5           | 5.26 ± 0.11   |
| 5             | 2.94 ± 0.12   |
| 10            | 1.72 ± 0.07   |

### Table 2. Standard deviation of counting system at the different times.

| Time (sec) | Standard deviation of counting system |
|------------|---------------------------------------|
| 30         | 0.40                                  |
| 60         | 0.28                                  |
| 120        | 0.20                                  |

Consequently the mean of the count rates obtained at a distance of 10 cm over a counting time of 120 s was plotted against bremsstrahlung photon energy as shown in Figure 5. A continuous spectrum was revealed between 35 keV and 500 keV with the peak at 44.2 keV (Figure 5).

![Bremsstrahlung spectrum of $^{90}$YCl$_3$ source measured by the NaI(Tl) scintillation detector (at 10 cm and 120 sec).](image)

#### Figure 5.

3.2. Simulation with MCNP

Monte Carlo simulation was primarily verified by comparison with the measurement of a $^{137}$Cs standard source. Figure 6 illustrates similarity of the $^{137}$Cs energy peak between experimental and simulated results when GEB is applied. However, experimental and simulated results were markedly different when GEB was not applied. Total count rates obtained experimentally by the NaI(Tl) scintillation detector and those obtained by MCNP simulation with GEB were in good agreement with a difference of 0.14%, well below the threshold of 2%.
Figure 6. Comparison of $^{137}$Cs peak among simulation with GEB (dash line), simulation without GEB (dotted line) and measurement with NaI(Tl) (bold line).

The Monte Carlo simulation code was created with the same geometry used in the measurement experiments. In Figure 7, the continuous simulated spectrum of the $^{90}$Y bremsstrahlung radiation with a peak at 40 keV is presented and compared to the spectrum obtained by scintillation detector measurements. The results of Monte Carlo simulations exhibited similar trend but certainly greater count rate was observed in simulations than in experiments (Figure 7). The difference between experimental and simulation results was 3.96 times based on area under the curve.

Figure 7. Bremsstrahlung spectrum of $^{90}$YCl$_3$ source produced from radiation shielding apparatus compared between measurement (bold line) and simulation (dash line).

4. Discussions

In this study, MCNP transport code was primarily validated by comparison of $^{137}$Cs gamma spectrum obtained experimentally by a NaI(Tl) detector and MCNP simulation. It is the characteristic of MCNP simulation that it simulates an ideal (theoretical) energy resolution for the detector, hence the single narrow peak was obtained as shown by the dotted line in Figure 6. This is markedly different from the experimental result obtained by the detector. Therefore, the 3 standard calibration sources in the energy range from 59.54 to 1332.50 keV were used to obtain a gamma ray spectrum and subsequently to determine $a$, $b$ and $c$ as FWHM parameters for GEB correction, as shown in equation (1) [7, 10, 11]. GEB was then applied in the FTn card of MCNP resulting in good agreement between experimental and simulated energy spectra for $^{137}$Cs (Figure 6).

$$FWHM = a + b \sqrt{E} + cE^2$$

Where $a$, $b$ and $c$ are parameters derived experimentally (see above) and $E$ is the gamma ray energy of the source (MeV).
Based on the basic performance and composition of the NaI(Tl) scintillation detector, photon emission with an energy below 50 keV could be entirely absorbed by the entrance surface (e.g. aluminium window) of the detector [2]. The general characteristic of bremsstrahlung radiation produced by high energy beta particles interacting with matter is a continuous spectrum with the most intensity at one-third of the maximum energy of the beta particle [2]. In Figure 7, the bremsstrahlung spectrum from MCNP5 simulation provided greater count rate than that of measurement by the NaI(Tl) scintillation detector. Both spectra have their peak intensity around 40 keV. At this low peak energy, the use of NaI(Tl) scintillation detector is suboptimal due to low detection efficiency and leads to lower count rates than those obtained by MCNP5 simulation. On the other hand, not only detector efficiency can cause a disagreement between empirical and MCNP5 simulation results: the simulation itself may also contribute to this discrepancy. Detector geometry is one of the most important factors that can influence the accuracy of the simulation. Chul-Young Yi et al. mentioned that an incomplete detector geometry model can lead to differences between experimental and simulation values [12]. Additionally, different types and versions of Monte Carlo codes could be more appropriate to be used in certain simulations than others [12-14]. A. Ho et al reported a good agreement between NaI(Tl) scintillation detector and GEANT4 simulation [13]. MCNP5 used in this study may not be suitable for simulating interaction of low energy radiation such as bremsstrahlung radiation. Recently, MCNP6 was launched and found to be more suitable for application in low energy photon/electron transport than MCNP5 [14]. Therefore in the future MCNP6 could diminish the difference between measurement and simulation.

5. Conclusion

This study demonstrated that $^{90}\text{Y}$ bremsstrahlung radiation can be produced from radiation shielding apparatus. Measurement technique using NaI(Tl) scintillation detector and Monte Carlo simulation, MCNP5, can be used to evaluate the $^{90}\text{Y}$ bremsstrahlung radiation. GEB should be applied to the MCNP5 transport code to improve simulation of a physical radiation detector. In addition, it is important that the related staff is made aware of $^{90}\text{Y}$ bremsstrahlung radiation and if necessary further radiation protection procedures will be implemented to reduce staff radiation exposure during SIRT.

References

[1] Khan FM and Gibbons JP 2014 Khan's the physics of radiation therapy (Philadelphia: Lippincott Williams & Wilkins) pp 256-258
[2] Cherry SR, Sorenson JA and Phelps ME 2012 Physics in nuclear medicine (Philadelphia: Elsevier)
[3] Knoll GF 2010 Radiation detection and measurement (Hoboken: John Wiley & Sons)
[4] McParland BJ 2010 Nuclear Medicine Radiation Dosimetry Advanced Theoretical Principles (London: Springer)
[5] Breur S 2013 Master's thesis, University of Amsterdam
[6] Akkurt I, Gunoglu K and Arda S 2014 Sci. Technol. Nucl. Install. 2014
[7] Salgado CM, Brandao LEB, Schirru R, Pereira CMNA and Conti CC 2012 Prog. Nucl. Energy 59 19-25
[8] Fantinova K, Fojtik P and Malatova I 2016 Radiat. Prot. Dosim. 170 354-8
[9] Ahmed Z and Darweesh M 2016 IOSR-JAP 8 130-3
[10] I. Mouhti AE and M Y. Messous 2017 J. Mater. Environ. Sci. 8 4560-5
[11] Zadeh EE, Feghhi S, Bayat E and Roshani G 2014 J. Exp. Theor. Phys. 2014 Physics. 2014;2014.
[12] Yi CY and Hah SH 2012 Appl. Radiat. Isot. 70 2133-6
[13] Ho A, Witharana SH, Jonkmans G, Li L, Surette R, Dubeau J and Dai X 2012 Radiat. Prot. Dosim. 151 443-9
[14] Hughes HG 2014 Prog. Nucl. Sci. Technol. 4 454-8