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ARTICLE

A study on calculation method of duct streaming from medical linac rooms

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The leakage radiation dose from medical linac systems must be suppressed to prevent public exposure to radiation. Therefore, leakage dose through ducts or sleeves installed in shielding walls need to be evaluated because radiation can pass through these without undergoing scattering or attenuation. However, conventional methods for calculating radiation streaming have not been sufficiently evaluated for the leakage dose from the ducts in mazes. In this study, the method provided by the Japan Radiological Society for neutrons and X-rays, Nakamura and Uwamino's formula for neutrons, the method described by the IAEA Safety Reports Series No.47 and the method given by McGinley for X-rays were evaluated by comparing the results with a Monte Carlo calculation using MCNP5 in calculation models. The rectangular ducts in these models were located in the maze near the entrance of linac room. Compared with MCNP5, most results for duct streaming obtained using conventional methods for neutrons were within a factor of 2, whereas the results of methods using X-rays were more than a factor of 2. The results for maze streaming using Nakamura and Uwamino's formula were in good agreement and differed by not more than 16%. Furthermore, the ratios of the X-ray dose at the duct entrance to that at the exit were calculated to investigate X-ray duct streaming with the results of MCNP5 and showed the relationships against the ratio of the opening area of the duct to square length.

Keywords: duct streaming; maze streaming; X-ray; neutron; Monte Carlo; radiotherapy; shielding design

1. Introduction

The number of cancer patients around the world is increasing, and medical linac systems are effective treatment tools for radiotherapy. When a medical linac is introduced at a facility, the leakage radiation from the linac room must be suppressed to prevent public exposure to radiation. For example, in Japan, the leakage radiation dose must be less than 1.3 mSv over a 3-month period at the boundary of the radiation controlled area. To suppress leakage of radiation of X-rays and neutrons to the outside of the room, thick radiation shields such as concrete walls and iron plates are used and a maze is placed between the irradiation room and the entrance. Therefore, methods for evaluating the leakage radiation dose are required to design appropriate shields. The leakage radiation dose through the shielding wall and maze streaming can be calculated numerically using the method described in IAEA Safety Reports Series No.47 [1]. The method considers operating conditions and room layout in the calculations. Conventional methods such as those provided by the Japan Radiological Society (JRS) [2], McGinley [3], and Nakamura and Uwamino [4] can also be used to evaluate the leakage radiation dose.

Heating, ventilation, and air conditioning ducts and sleeves for cables installed through the shielding walls are also important structures to consider for the calculation of leakage radiation dose from a linac room. The leakage radiation doses through them must be evaluated because radiation can pass through these without undergoing scattering or attenuation, which may result in relatively high doses. The Duct-III code [5], which is based on Shin's semi-empirical formula [6], is a calculation tool for radiation streaming and is often used to estimate duct streaming. However, the methods can overestimate or underestimate the leakage radiation dose when the streaming path is complicated. In this case, a Monte Carlo calculation such as MCNP5 [7] may provide calculations with better accuracy; however, such methods require a much longer calculation time and skills.

Although conventional streaming calculation methods are advantageous because their operation is easy and fast, they have not been sufficiently evaluated for the leakage radiation dose from the duct in the maze. In this study, conventional numerical calculation methods, such as the method provided by JRS for calculating leakage dose of neutrons and X-rays, Nakamura and Uwamino's formula for calculating leakage dose of neutrons, the method described in IAEA Safety Reports Series No.47, and the McGinley method for calculating leakage dose of X-rays are evaluated by comparing the obtained results with MCNP5.

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2. Calculation methods

2.1. Linac system and room layout

A linac system with an energy of 10 MeV is assumed for the calculation model since this is the most common system in Japan. The irradiation conditions of the model are an accelerator workload of 60,000 Gy over 3 months at an isocenter that is 1 m away from the target in the linac head, an absorbed dose to water of 6 Gy/min at the isocenter, a field size of primary beam of 0.40 × 0.40 m^2 at the isocenter, and the ratio of the dose sourced from head leakage relative to the primary beam of 0.001 that is conservative upper limit of regulated value in ordinance for enforcement of the medical care act in Japan. The linac head is located parallel to the maze (**Figure 1**). The room height is 3.05 m, and the beam is at a height of 1.295 m from the floor. A rectangular duct with opening areas of 0.10 × 0.10, 0.20 × 0.20, or 0.30 × 0.30 m^2 and lengths of 0.70, 1.0, or 1.3 m is installed on the maze wall near the entrance at the same height as the beam. The dose rates at the maze corner (A), the center of the maze on the duct axis (B), the duct entrance (C) for maze streaming, and the duct exit (D) for duct streaming were calculated. Scattering radiation from the patient was ignored in this calculation.

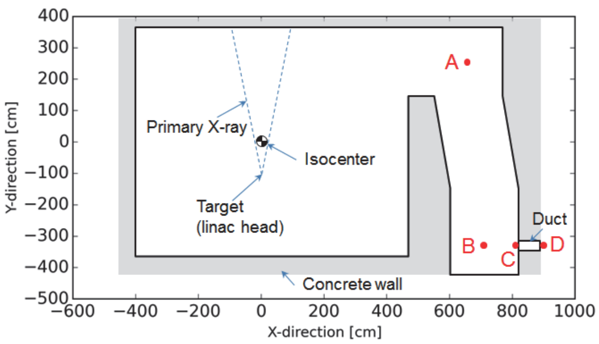

Figure 1. Study room layout and calculation points A, B, C, and D.

2.2. Neutron streaming

2.2.1 JRS method

The equation for calculating the neutron dose rate E at a scattered point is given as

$$E = \frac{E'\alpha_1 A_1}{(d_0 d_1)^2} \times 1.43 \quad (1)$$

where E' is neutron dose rate at a point 1.0 m away from the target and is calculated by multiplying the workload of the accelerator by the ratio of 1.5 × 10^{-4} Sv/Gy for a 10 MeV linac with a copper target [3]. A_1 is scattering area, d_0 and d_1 are the distances from the target to scattering area and from the scattering area to calculation point, respectively, and 1.43 is a factor that accounts for the contribution of thermal and fast neutrons. The reflection coefficient α_1 can be calculated by the equation

$$\alpha_1 = 0.11(\cos\theta_0)^{2/3}\cos\theta \quad (2)$$

where θ_0 is the incident angle and θ is the reflection angle. For a multi-scattered path, Eq. (1) may be modified by multiplying with a factor of $\alpha_i A_i/d_i^2$ for leg i.

2.2.2 Nakamura and Uwamino's formula

This method evaluates the dose at the first leg in the maze (point A in Figure 1) with

$$E_0 = E'\left(\frac{1}{r^2} + \frac{\alpha}{r^2 + 4s^2 - 2\sqrt{2}rs} \times \frac{A'}{A}\right),$$

$$s = \frac{\sqrt{L_1 L_2}}{2} \quad (3)$$

where E' is the neutron dose rate at a point 1.0 m away from the target, r is distance between the target and the evaluation point, A is the total surface area of the irradiation room, A' is the surface area of the irradiation room seen directly from the evaluation point, L_1 and L_2 are the width and length of the irradiation room, respectively, and α is an adjustable parameter. E' was calculated by MCNP5 at the isocenter. The parameter α was set to a value of 0.5 in this study by comparing with the result of MCNP5, whereas study [4] used a value of 4 by comparing with the results of DOT 3.5.

The dose rate E_i at the evaluation point for ith leg was calculated by the equation

$$E_i = E_{i-1}\frac{a_i^2}{r_i^2} \quad (4)$$

where r_i is the distance of ith leg and a_i is the half width of the maze or the duct. The evaluation points on the streaming path were located at a distance of a_i away from the entrance of the maze or the duct.

2.3. X-ray streaming

2.3.1 IAEA safety reports series No.47 and McGinley methods

The X-ray streaming paths from the target are categorized as the primary beam scattered by the wall into the maze (E_W), the head leakage radiation scattered by the wall into the maze (E_L), and the head leakage radiation transmitted through the maze (E_T). The primary beam transmitted through the maze and photons generated by the interaction of neutrons are negligible for a linac system with an energy of 10 MeV. E_W, E_L, and E_T are calculated using the equations

$$E_W = \frac{W\alpha_{W1}A_{W1}}{(d_{W0}d_{W1})^2} \quad (5)$$

$$E_L = \frac{WL_0\alpha_{L1}A_{L1}}{(d_{L0}d_{L1})^2} \quad (6)$$

$$E_T = \frac{WL_0 B}{d_T^2} \quad (7)$$

where W is the workload of the accelerator, L_0 is the ratio of the dose generated by head leakage at 1.0 m from the target to the dose at the isocenter, α_{W1} and α_{L1} are reflection coefficients described in references [1, 3], and d_{W0}, d_{W1}, d_{L0}, d_{L1}, and d_T are the distances of the legs from the target or scattering points. The equation for calculating the barrier transmission factor B is

$$B = 10^{-\frac{t}{TVL}}, \quad (8)$$

where t is the wall thickness and TVL is the tenth value layer of the wall material. For multi-scattered paths, Eqs.(5) and (6) may be modified by multiplying by a factor of $(\alpha_i A_i/d_i^2)$ for leg i, which is similar to Eq.(1).

2.3.2 JRS method

The streaming paths considered for E_W, E_L, and E_T are similar to those described previously. E_W and E_L are calculated using Eqs. (5) and (6) by multiplying with a safety factor of 2 and 1.43 Sv/Gy, respectively, with a constant reflection coefficient of 0.01. E_T is calculated using Eq. (7). The equation for calculating B is

$$B = F_0 \times 10^{-\frac{t}{TVL}}, \quad (9)$$

where F_0 is the correction factor described in reference [2].

2.4. Monte Carlo calculation

MCNP5 was used to calculate the dose rate. The calculations were separated into two steps to distinguish radiation type and paths.

Firstly, spectra of the neutron, primary X-ray, and head leakage X-ray spectra shown in **Figure 2** were calculated using a simplified linac head model. A copper target with 15-mm thickness was irradiated with monoenergetic electrons with an energy of 10 MeV to generate X-rays and neutrons, which were tallied at the isocenter. A tungsten collimator was located around the target to reduce the dose rate of head leakage to 1/1000 of the primary X-ray dose rate. The head leakage X-ray was tallied at a point 1.0 m away from the target at 90° to the beam axis.

In the second step, transport calculations of neutrons, primary X-rays, head leakage X-rays, and the head leakage X-rays transmitted through the maze wall without entering aperture of the maze were performed separately. The dose rates were normalized to the absorbed dose in water at the isocenter, which is 6 Gy/min for primary X-rays. **Figure 3** shows the dose map of the primary X-rays. The dose rates of the head leakage X-rays scattered on the wall were calculated by

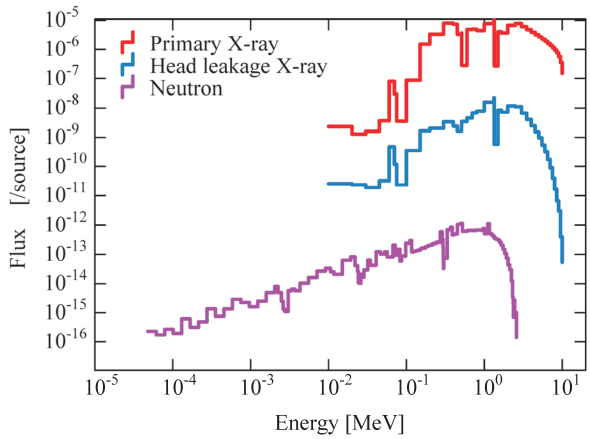

Figure 2. Spectra of primary X-rays, head leakage X-rays, and neutrons.

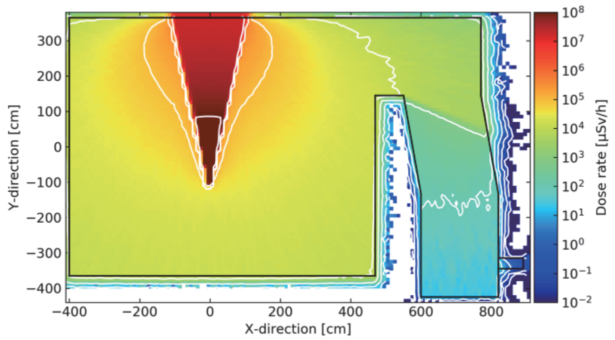

Figure 3. Dose map of primary X-ray irradiation.

subtracting the dose rate of the head leakage X-ray transmitted through the maze wall from that of the whole head leakage X-rays.

3. Results and discussion

3.1. Evaluation of conventional methods

The results of the neutrons streaming through the maze are shown in **Figure 4 (a)**, and the results of the neutrons streaming through the duct are shown in **Figures 4 (b)-(d)**. Statistical errors of dose rates in the MCNP calculations were less than 2%. The duct streaming results were within a factor of 2 from the MCNP5 results, except at low dose rates or for an opening area of 0.10^2 m^2 with duct lengths of 1.0 or 1.3 m.

Compared with maze streaming, the results of Nakamura and Uwamino's formula differed by not more than 16%, whereas the results of the JRS method were overestimated by at least a factor of 6.

The results of X-rays streaming through the maze are shown in **Figures 5 (a)-(c)**, and duct streaming of X-rays is shown in **Figures 5 (d)-(l)**. Statistical errors of dose rates in MCNP calculations were less than 5%. The E_L values of the McGinley method were within a factor of 2, whereas other streaming paths were dissimilar by at least a factor of 2 from the MCNP results. The JRS method and the method from the IAEA Safety Reports Series No.47 also contained results that were overestimated by a factor of 2 compared with MCNP5. Therefore, these methods can overestimate and underestimate the shielding design.

3.2. Duct streaming ratio

The ratios of the X-ray dose at the duct entrance to that at the exit were also calculated to investigate X-ray duct streaming. As the opening area of the duct (A_D) was enlarged or the length was (L_D) shortened, the X-ray dose at the duct exit increased. The streaming ratio of the primary X-ray (R_W), head leakage X-ray scattered by the wall (R_L), and head leakage X-ray transmitted through the maze (R_T) was plotted against A_D/L_D^2 in **Figure 6**. Opening areas of ducts of 0.40^2, 0.50^2 and 0.60^2 m^2 were also calculated. Statistical errors in these additional calculations were less than 3%. R_W and R_L exhibited a linear relationship with A_D/L_D^2, whereas R_T

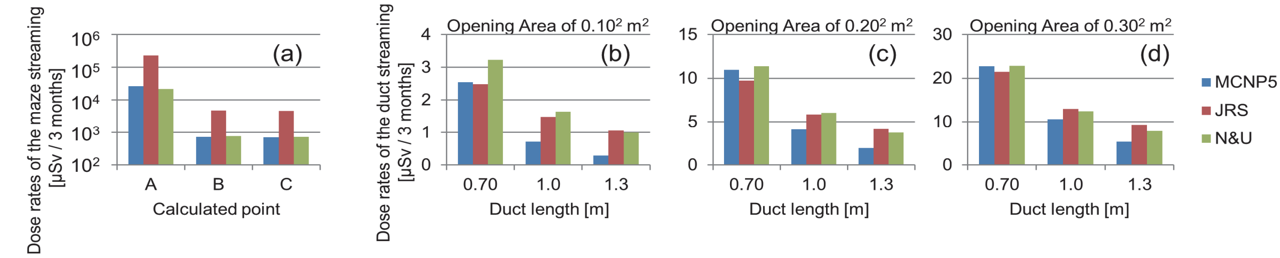

Figure 4. Results of (a) maze streaming and (b)-(d) duct streaming of neutrons. N&U stands for Nakamura & Uwamino's formula.

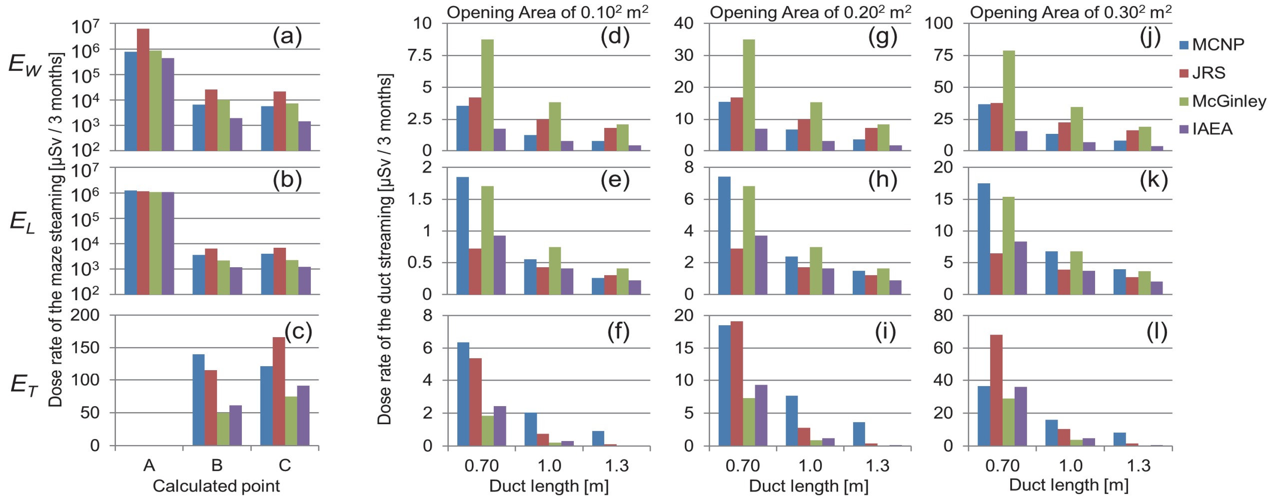

Figure 5. Results of maze streaming (a)-(c) and duct streaming (d)-(l) of X-ray. Streaming paths of (a), (d), (g), and (j) are E_W, (b), (e), (h), and (k) are E_L and (c), (f), (i), and (l) are E_T.

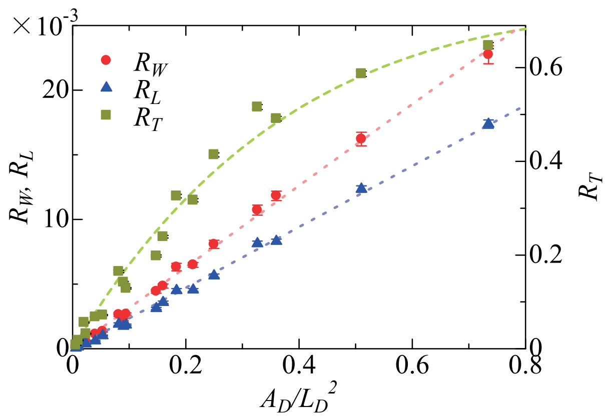

Figure 6. Plots of streaming ratios R_W, R_L, and R_T against A_D/L_D^2 and fitting lines.

was found to be related to the saturation curve. Based on these results, the dose rates at the duct exit may be calculated by multiplying the streaming ratios R_W, R_L, and R_T to the doses at the duct entrance, which is calculated using conventional streaming methods. These calculations may use improved maze streaming method in the future. However, these ratios should be analyzed for the effects of changing the room layout, such as changing the irradiation room size, maze geometry, and duct position, and then used to calculate duct streaming.

4. Conclusions

Conventional streaming calculation methods for neutrons, primary X-rays, head leakage X-rays scattered by the wall, and head leakage X-rays transmitted through the maze were evaluated by comparing them with the results from MCNP5 for the duct in the maze in a 10 MeV linac room. The results from Nakamura and Uwamino's formula for neutron streaming were within a factor of 2 at the evaluation points in the maze and the duct. The results from the X-ray streaming methods were overestimated by at least a factor of 2. The MCNP5 results also yielded the relation of streaming ratios, which is the ratio of the dose at the duct entrance to that at the exit, against the ratio of the duct opening area to square length. The dose rates at the duct exit may be calculated by multiplying the streaming ratios to the doses at the duct entrance.

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