Bremsstrahlung and Photoneutron Leakage from Steel Shielding Board Impinged by 12-24 MeV Electrons Beams

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Radiation shield/Leakage dose/Photoneutron/Bremsstrahlung/Electron beam.

Many medical linear accelerators generate not only high-energy photons, but also high-energy electrons, and they are no longer equipped with beam stoppers. Therefore, shields might be necessary against bremsstrahlung and photoneutron generated by high-energy electron beams. However, there are few physical studies, and no recommendations are made about shields nowadays. In this report, the leakage doses of bremsstrahlung and photoneutron were calculated by the use of Monte Carlo simulation. To verify the calculated results, the photoneutron leakage dose was measured with a rem counter. The results clearly show that the bremsstrahlung and photoneutron leakage dose generated by electron beams of 24 MeV or below is negligible.

INTRODUCTION

In the aim of radiotherapy, the spatial distribution of the prescribed dose should be conformed to the target volume, and the dose to the surrounding normal tissue should be minimized. Radiotherapy planning and delivery are in the process of dramatic changing, so that higher degree of freedom regarding to gantry angle and coach position is required for the sophisticated and complicated delivery techniques, such as 3D-CRT. A linear accelerator (linac) equipped with a beam stopper has been dropped from an option because of the reason above mentioned nowadays.

In the last year, our previous linac, which generates 6 MV X-ray and 6 MeV electrons and equipped with a beam stopper, was to be replaced with a new one which generates 6 MV X-ray and maximum energy of 15 MeV electrons. The new linac is not equipped with a beam stopper, so that the shielding wall should be reinforce instead of a beam stopper.

The radiation shield for the linac room was designed in accordance with the “Manual of Practical Shield Calculation for Radiation Facilities” (Manual) in Japan.1) In the first plan, according as the Manual, the shielding wall was reinforced by means of adding steel boards to the inside of concrete wall as shown in the Fig. 1-(a, b). However, the competent authorities pointed out the necessity of shielding against bremsstrahlung and photoneutron generated by the interaction between electrons and the steel boards. Therefore, the reinforce plan was changed to adding plaster boards in front of the steel boards as shown in the Fig. 1-(c) because radiation loss decreases as the electron kinetic energy, constituent of plaster board; H, O, S and Ca has lower atomic number than Fe and has higher threshold energy of photonuclear reaction than 15 MeV. On the other hand, there are few physical data and no recommendations about shields for bremsstrahlung and photoneutron generated by the interaction between electrons and the steel boards or the plaster boards in the Manual.

Our aim in this report was to clarify the leakage dose of bremsstrahlung and photoneutron from the steel board and the plaster board caused by high-energy electron beams for radiotherapy, and to provide the physical data for shielding design.

METHODS AND MATERIAL

Calculation of Bremsstrahlung Leakage Dose

In this report, the leakage doses were calculated by the Electron Gamma Shower (EGS) Monte Carlo code2) because it was difficult to measure the leakage dose from shielding walls of various thicknesses. Table 1 shows the composition of several different shielding materials. This data was used to calculate cross-sectional data by means of the Preprocessor for EGS code (PEGS).2) For simulations, the primary electron energy was assumed to be monoenergetic at 12, 15, 18, 20, 22 and 24 MeV. Those electron energies can be accelerated by a general medical linac. For all simulation conditions, 2 × 10^9 incident electrons were used to get a statistical uncertainty of less than 5%.

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doi:10.1269/jrr.090016
Figure 2 shows the simulation geometry for calculation of the average energy fluence of the leakage bremsstrahlung at energy $E_p$ per primary electron. The average energy fluence is normalized by number of incident particles $NP$, and the average fluence is calculated following equation,

$$\overline{\Phi}(E_p) = \frac{E_p \Phi(E_p)}{NP}$$

(1)

where $\Phi(E_p)$ is the bremsstrahlung fluence at energy $E_p$. This geometry was modeled after the shielding wall of our reinforcement plan. The thickness of steel board and concrete is 17 cm and 120 cm, respectively. This thickness corresponds to a total of 6 tenth value layer (TVL) for a 6 MV X-ray. The transmitted bremsstrahlung were sampled at the position of scoring plane shown in Fig. 2 and spectra and fluence of bremsstrahlung in the restricted area including evaluation point of leakage dose were determined.

To calculate the actual energy fluence of the leakage bremsstrahlung, it was necessary to estimate the numbers of primary electron incident on the steel board. Therefore, at first, the electron fluence rate $\Phi_{\text{elec}}$ at the isocenter was calculated by,

$$\Phi_{\text{elec}} = D_{\text{water}} \left( \frac{S_{\text{col}}(E_e)}{\rho} \right)_{\text{water}}^{-1}$$

(2)

where $D_{\text{water}}$ is the absorbed dose rate at isocenter and $(S_{\text{col}}/\rho)_{\text{water}}$ is the mass collision stopping power for water at electron energy $E_e$. Then, the energy fluence rate $\Psi(E_p)$ of the leakage bremsstrahlung was calculated from the average energy fluence $\overline{\Phi}(E_p)$ per primary electron and the electron fluence rate $\Phi_{\text{elec}}$ at the isocenter,

$$\Psi(E_p) = \overline{\Phi}(E_p) \Phi_{\text{elec}} \left( \frac{d_{\text{IC}}}{d_{\text{wall}}} \right)^2$$

(3)

where, $d_{\text{IC}}$ is the source to isocenter distance, and $d_{\text{wall}}$ is the source to wall distance.

Consequently, the collision kerma rate $K_{\text{col}}$ which may leak from the shielding wall was calculated by,

$$K_{\text{col}} = \int_{E_p}^{E_{\text{max}}} \left( \frac{\mu_{\text{en}}(E_p)}{\rho} \right)_{\text{air}} \Psi(E_p) dE_p$$

(4)
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where, \((\mu_{en}(E_p)/\rho)_{air}\) is the mass energy absorption coefficient at bremsstrahlung energy \(E_p\) for ambient air.\(^4\)

**Calculation of Photoneutron Leakage Dose**

The EGS code is unfortunately impossible to simulate a photonuclear interaction. Therefore photoneutron leakage dose was determined by following three steps.

**Calculation of bremsstrahlung spectra in steel board and plaster board**

At first, the energy spectrum of bremsstrahlung above the threshold energy of a photonuclear reaction was calculated by the EGS code. Table 2 shows the threshold energy of photonuclear reaction for several elements which are ingredients of shielding materials.\(^5\) According to the Table 2, photoneutron can be emitted when bremsstrahlung energy is above 11.2 MeV. Therefore, the primary electron energy was assumed to be monoenergetic at 12, 15, 18, 20, 22 and 24 MeV and the bremsstrahlung above 11.2 MeV were sampled. For all simulation conditions, \(5 \times 10^8\) incident electrons were used to get a statistical uncertainty of less than 1%.

Figure 3 shows the simulation geometries for calculation of the average bremsstrahlung fluence per primary electron \(\Phi_{\text{brems}}(E_p)\) which was generated in (a) steel board and (b) plaster board. In Fig. 3-(a), thicknesses of the steel board \(t_{\text{steel}}\) which generate bremsstrahlung above 11.2 MeV was calculated by,

\[
t_{\text{steel}} = \int_{11.2}^{E_0} \left( \frac{S_{\text{tot}}(E_e)}{\rho} \right)_{\text{steel}}^{-1} dE_e
\]

where, \(E_0\) is initial electron energy, \((S_{\text{tot}}(E_e)/\rho)_{\text{steel}}\) is the total mass stopping power for the steel board and \(E_e\) is electron energy. In Fig. 3-(b), the thickness of plaster board was calculated from the effective electron range \(R_{\text{eff}}\). \(R_{\text{eff}}\) can be calculated by,\(^1\)

\[
R_{\text{eff}} = (0.530 E_e - 0.106) \frac{\rho_{\text{water}}}{\rho_{\text{shield.m}}}
\]

where \(E_e\) is a electron energy, \(\rho_{\text{water}}\) and \(\rho_{\text{shield.m}}\) are density of water and shielding material, respectively. For 15 MeV electrons, \(R_{\text{eff}}\) is 6.54 cm in the plaster board with density 1.2 g/cm\(^3\), so that plaster board of 7.5 cm is sufficient of shielding thickness for attenuation of 15 MeV electrons. For 24 MeV electrons, \(R_{\text{eff}}\) is 10.5 cm in the plaster board. However, the electron energy was reduced below 11.2 MeV by the plaster board of 7.5 cm. Therefore, for all simulation conditions, the thickness of plaster board was only 7.5 cm.

Figure 4 shows the cross section of photonuclear reaction for the steel board and the plaster board.\(^5\) According to Fig. 4, the cross section of photonuclear reaction for plaster board is a tenth of the steel board. Furthermore, the radiation loss in plaster board is lower than steel board because plaster board consist of low atomic number element. The photoneutron fluence which generated in shielding materials depends on the cross section of photonuclear reaction and the bremsstrahlung fluence above the threshold energy of a photonuclear reaction. Therefore, it was assumed that the photoneutron which is generated in plaster board was ignored and the photoneutron was generated from only steel board in this report.

**Table 2.** Threshold energy of photonuclear reaction for several materials.\(^5\)

| Element | Threshold energy [MeV] |
|---------|----------------------|
| C       | 18.72                |
| O       | 15.66                |
| Mg      | 16.53                |
| Al      | 13.06                |
| Si      | 17.18                |
| S       | 15.04                |
| Ca      | 15.64                |
| Fe      | 11.20                |

**Fig. 3.** Simulation geometry for calculation of bremsstrahlung fluence distribution in (a) steel boards and (b) plaster boards.

**Fig. 4.** The cross section of photonuclear reaction of the steel board and the plaster board as function of photon energy.
The simulated bremsstrahlung fluence was averaged over the number of incident electrons. Therefore, to convert the simulated bremsstrahlung fluence to the actual fluence, it was necessary to estimate the numbers of primary electrons. At first, the electron fluence rate \( \Phi_{\text{elec}} \) at the isocenter was calculated by equation (2), and the actual fluence rate of bremsstrahlung \( \Phi_{\text{brems}}(E_p) \) was calculated by the following equation,

\[
\Phi_{\text{brems}}(E_p) = \Phi_{\text{elec}}(E_p) \frac{dE}{d\text{IC}} \left( \frac{d^2}{d\text{wall}} \right)^2
\]  

(7)

where, \( \Phi_{\text{elec}}(E_p) \) is the average fluence per primary electron, \( dE \) is the source to isocenter distance, and \( d\text{wall} \) is the source to wall distance.

**Calculation of photoneutron spectra**

Secondly, the photoneutron spectrum which was generated in steel board was calculated by the bremsstrahlung spectra and the cross section of photoneutron reaction. The total number of interactions in the steel board \( \Delta N \) is given by,

\[
\Delta N = N_0 \left[ 1 - e^{-\left(\frac{\mu_{\text{at}}(E_p)}{\rho}\right)} \right]
\]

(8)

where \( N_0 \) is the number of primary photon and \( \mu_{\text{at}}(E_p) / \rho \) is the total mass attenuation coefficient for the shielding material, \( t \) is mass thickness of a shielding material and \( E_p \) is photon energy. Therefore, the photoneutron fluence rate \( \Phi_{\text{ph.n}}(E_p) \) at photon energy \( E_p \) in steel board was calculated by,

\[
\Phi_{\text{ph.n}}(E_p) = \Phi_{\text{brems}}(E_p) \left[ 1 - e^{-\left(\frac{\mu_{\text{at}}(E_p)}{\rho}\right)} \right] \frac{\sigma_{\text{ph.n}}(E_p)}{\sigma_{\text{at}}(E_p)}
\]

(9)

where, \( \Phi_{\text{brems}}(E_p) \) is the primary fluence rate of the bremsstrahlung, \( \mu_{\text{at}}(E_p) / \rho \) is the total cross section of a photoneutron reaction at photon energy \( E_p \).

The \( \mu_{\text{at}} / \rho \) data calculated by J.H. Hubbell and S.M. Seltzer do not contain cross section of a photoneutron reaction. In this report, the \( \mu_{\text{at}}(E_p) / \rho \) data which contains a photoneutron reaction was calculated by,

\[
\frac{\mu_{\text{at}}(E_p)}{\rho} = \frac{\sigma_{\text{at}}(E_p)}{uA} \frac{\sigma_{\text{H.S.}}(E_p) + \sigma_{\text{ph.n}}(E_p)}{uA}
\]

(10)

where \( \sigma_{\text{at}}(E_p) \) is the total cross section calculated from the total mass attenuation coefficient calculated by J.H. Hubbell and S.M. Seltzer and \( \sigma_{\text{ph.n}}(E_p) \) is the cross section of a photoneutron reaction by the Japanese Evaluated Nuclear Data Library (JENDL) Photonnuclear Data File at photon energy \( E_p \). \( u \) is an atomic mass constant (\( 1.6605402 \times 10^{-24} \text{ g}^6 \)) and \( A \) is the relative atomic mass.

The energy of the photoneutron could not specify in equation (9), therefore, the photoneutron energy \( E_{\text{ph.n}} \) was determined by the following equation,

\[
E_{\text{ph.n}}(\theta) = \frac{M(E_p + Q)}{m + M} + \frac{1}{(m + M)^2} \left( 2mM \right) \frac{E_p}{(m + M)} (m + M)(E_p + Q) \cos \theta
\]

(11)

where \( \theta \) is the angle between the primary photon to the recoil neutron direction, \( E_p \) is the photon energy (\( E_p \ll 931 \text{ MeV} \)), \( Q \) is Q-value which is the amount of energy produced in a photoneutron reaction, \( M \) and \( m \) are the rest mass of the recoil nucleus and the neutrons in MeV.

**Calculation of photoneutron spectra**

Finally, the leakage photoneutron kerma rate \( K_{\text{ph.n}} \) was calculated by the following equation,

\[
K_{\text{ph.n}} = \int_0^{E_{\text{max}}} \Phi_{\text{ph.n}}(E_{\text{ph.n}}) k(E_{\text{ph.n}}) F_n(E_{\text{ph.n}}) dE_{\text{ph.n}}
\]

(12)

where \( k(E_{\text{ph.n}}) \) is the kerma coefficient which is given by ICRU report 26 and \( F_n(E_{\text{ph.n}}) \) is the effective dose transmission coefficient of a concrete for the neutron at neutron energy \( E_{\text{ph.n}} \).

**Leakage Dose Measurement**

To verify the calculated results, the photoneutron leakage dose was measured with a rem counter (2202D, ALONOR) when the shield wall was irradiated with 12 MeV and 15 MeV electron beams at a maximum dose rate of 10 Gy/min. The photoneutron leakage dose was measured only in the case of adding the plaster board because the construction of the final reinforcement plan was completed at the measurement.

**RESULTS AND DISCUSSIONS**

**Leakage Dose of Bremsstrahlung**

Figure 5 shows the energy fluence distribution of the leakage bremsstrahlung calculated by Monte Carlo simulations. The energy fluence was averaged over the number of incident electrons.

The air collision kerma rate when electron beam was irradiated with maximum dose rate 10 Gy/min was calculated by using the energy fluence distribution and equation (4). The calculated results were shown in Table 3. In Table 3, the air collision kerma rate was converted into effective dose per 10 Gy which is irradiation dose limit per 3 months period in our institution. The effective dose limit for controlled area is 1.3 mSv per 3 months period in Japan. According to Table 3, the leakage dose of bremsstrahlung was quite less than the dose limit.

**Leakage Dose of Photoneutron**

Figure 6 shows the energy spectra of the bremsstrahlung...
above 11.2 MeV which was generated (a) in the steel board and (b) in the plaster board. The fluence was averaged over the number of incident electrons. The fluence of bremsstrahlung above 11.2 MeV was less than 10% of the total fluence in steel board even if the incident electron energy was 24 MeV. In the case of plaster board as primary shield, the bremsstrahlung fluence was a half of fluence from the steel board because the radiation loss is small at lower atomic number.

In this report, the leakage dose was estimated to be on the safe side. The depth where the photoneutron was generated could not be specified by equation (9), therefore the attenuation of the photoneutron in the steel board was ignored. And the photoneutron energy depends on scattered angle $\theta$ by equation (11), but photoneutron was assumed to be projected forward with maximum energy.

Figure 7 shows the energy spectra of the photoneutron which were calculated from the fluence distribution as shown in Fig. 6 and equations (9, 11). The photoneutron yield depends on the fluence above the threshold energy of a photonuclear reaction. Therefore, in the case of plaster board, the photoneutron fluence was half of steel board.

Air collision kerma at the maximum dose rate of electron beam and effective dose of the leakage bremsstrahlung per 10$^4$ Gy was tabulated in Table 4 and Table 5, respectively. These leakage doses were calculated by the energy spectra of the leakage photoneutron which were shown in Fig. 7 and equation (12). The leakage dose was reduced to about a half by adding of the plaster board.

Comparison between Measured and Calculated Leakage Doses

Table 6 shows the calculated and measured leakage doses of bremsstrahlung and photoneutron. The rem counter can measure only dose by neutrons and its detection limit was 1 $\mu$Sv/h. According to the Table 6, the calculated leakage dose
was quite less than the detection limit and photoneutron leakage was not detected by the rem counter as expected.

**Total Leakage Dose**

Table 7 shows the leakage dose of bremsstrahlung, photoneutron and total per $10^4$ Gy when steel board was used as primary shield. According to Table 7, the total leakage dose was less than a hundredth of the effective dose limit, 1.3 mSv per 3 months period, even if steel board was used for primary shield of 24 MeV electrons.

It is obvious that the leakage dose was incomparably less than the dose limit for a controlled area under all calculation conditions whether plaster boards were placed in front of the steel board or not. The bremsstrahlung and photoneutron leakage dose generated from the steel board as shield wall is quite negligible for electrons of 24 MeV or below.

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**Table 4.** Air collision kerma rate of the leakage photoneutron at a maximum dose rate of 10 Gy/min.

| Electron energy [MeV] | Steel board + Concrete [Gy min⁻¹] | Plaster board + Steel board + Concrete [Gy min⁻¹] |
|-----------------------|----------------------------------|-----------------------------------------------|
| 12                    | $1.74 \times 10^{-15}$           | $6.36 \times 10^{-16}$                         |
| 15                    | $1.19 \times 10^{-12}$           | $4.75 \times 10^{-13}$                         |
| 18                    | $3.44 \times 10^{-11}$           | $1.47 \times 10^{-11}$                         |
| 20                    | $1.05 \times 10^{-10}$           | $4.71 \times 10^{-11}$                         |
| 22                    | $2.26 \times 10^{-10}$           | $1.06 \times 10^{-10}$                         |
| 24                    | $4.01 \times 10^{-10}$           | $1.97 \times 10^{-10}$                         |

**Table 5.** Effective dose of the leakage photoneutron [mSv / 3-month/10⁴ Gy at the isocenter].

| Electron energy [MeV] | Steel board + Concrete [mSv / 3-month] | Plaster board + Steel board + Concrete [mSv / 3-month] |
|-----------------------|---------------------------------------|-------------------------------------------------------|
| 12                    | $3.72 \times 10^{-8}$                 | $1.27 \times 10^{-8}$                                 |
| 15                    | $1.41 \times 10^{-5}$                 | $5.61 \times 10^{-6}$                                 |
| 18                    | $3.50 \times 10^{-4}$                 | $1.49 \times 10^{-4}$                                 |
| 20                    | $1.06 \times 10^{-3}$                 | $4.74 \times 10^{-4}$                                 |
| 22                    | $2.27 \times 10^{-3}$                 | $1.07 \times 10^{-3}$                                 |
| 24                    | $4.02 \times 10^{-3}$                 | $1.98 \times 10^{-3}$                                 |

**Table 6.** Comparison between calculated and measured leakage doses.

| Electron energy [MeV] | Steel board + Concrete [μSv h⁻¹] | Plaster board + Steel board + Concrete [μSv h⁻¹] |
|-----------------------|---------------------------------|-------------------------------------------------|
| Photoneutron (calculated) | $1.04 \times 10^{-10}$ | $3.82 \times 10^{-11}$ |
| Measured              | $7.17 \times 10^{-8}$          | $2.85 \times 10^{-8}$ |

The detection limit of the rem counter is 1 μSv/h.

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**Fig. 7.** Energy spectrum of the photoneutron in the case of primary shield of (a) steel boards and (b) plaster boards.
CONCLUSIONS

To clarify the bremsstrahlung and photoneutron leakage dose by irradiation of high-energy electron beams used in radiotherapy, the leakage dose was calculated by using Monte Carlo simulations and theoretical calculation. The presented results indicate the bremsstrahlung leakage dose is few contributions to total leakage dose and photoneutron leakage dose is quite less than the dose limit. Therefore, the bremsstrahlung and photoneutron leakage dose which is generated by electrons of 24 MeV or below is negligible when shield is reinforced by adding steel board to inside of the treatment room. The recommendation, based the presented data, is that it is adequate to reinforce a shield by use of only a steel board to the inside walls of the treatment room.

| Electron energy [MeV] | Bremsstrahlung [mSv / 3-month] | Photoneutron [mSv / 3-month] | Total [mSv / 3-month] |
|-----------------------|-------------------------------|-------------------------------|----------------------|
| 12                    | $2.43 \times 10^{-9}$         | $3.48 \times 10^{-8}$         | $3.72 \times 10^{-8}$ |
| 15                    | $6.01 \times 10^{-9}$         | $1.41 \times 10^{-5}$         | $1.41 \times 10^{-5}$ |
| 18                    | $1.17 \times 10^{-8}$         | $3.50 \times 10^{-4}$         | $3.50 \times 10^{-4}$ |
| 20                    | $1.67 \times 10^{-8}$         | $1.06 \times 10^{-3}$         | $1.06 \times 10^{-3}$ |
| 22                    | $2.25 \times 10^{-8}$         | $2.27 \times 10^{-3}$         | $2.27 \times 10^{-3}$ |
| 24                    | $2.93 \times 10^{-8}$         | $4.02 \times 10^{-3}$         | $4.02 \times 10^{-3}$ |

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Received on February 9, 2009
Revision received on May 9, 2009
Accepted on May 11, 2009
J-STAGE Advance Publication Date: June 20, 2009