Evaluation of beam hardening and photon scatter by brass compensator for IMRT

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When a brass compensator is set in a treatment beam, beam hardening may take place. This variation of the energy spectrum may affect the accuracy of dose calculation by a treatment planning system and the results of dose measurement of brass compensator intensity modulated radiation therapy (IMRT). In addition, when X-rays pass the compensator, scattered photons are generated within the compensator. Scattered photons may affect the monitor unit (MU) calculation. In this study, to evaluate the variation of dose distribution by the compensator, dose distribution was measured and energy spectrum was simulated using the Monte Carlo method. To investigate the influence of beam hardening for dose measurement using an ionization chamber, the beam quality correction factor was determined. Moreover, to clarify the effect of scattered photons generated within the compensator for the MU calculation, the head scatter factor was measured and energy spectrum analyses were performed. As a result, when X-rays passed the brass compensator, beam hardening occurred and dose distribution was varied. The variation of dose distribution and energy spectrum was larger with decreasing field size. This means that energy spectrum should be reproduced correctly to obtain high accuracy of dose calculation for the compensator IMRT. On the other hand, the influence of beam hardening on $k_Q$ was insignificant. Furthermore, scattered photons were generated within the compensator, and scattered photons affect the head scatter factor. These results show that scattered photons must be taken into account for MU calculation for brass compensator IMRT.

Keywords: Brass compensator IMRT; beam hardening; dose distribution; quality correction factor; scatter photon

INTRODUCTION

Intensity modulated radiation therapy (IMRT) has come into wide use recently [1]. As a means of intensity modulation, the multileaf collimator (MLC) or compensation filter (compensator) is utilized [2]. The compensator technique has multiple advantages in comparison with the MLC technique [3]. Intensity modulation can be performed with higher resolution and smoother dose distribution, in consequence problems originating from patient movement can be minimized. Furthermore, the monitor unit (MU) can be reduced because multiple segments are unnecessary [4]. Production of a compensator used to be a troublesome job, however outside supply and delivery systems are available nowadays. Therefore compensator IMRT has become a realistic possibility.
With brass compensator IMRT, the photon energy spectrum can be varied downstream of the compensator because of beam hardening or softening. In the dose calculation using the convolution/superposition algorithm, the effective attenuation coefficient and dose kernel may be changed for calculation of TERMA and dose distribution. And in the absorbed dose measurement, the quality correction factor for the ionization chamber may be changed.

Furthermore, when X-rays pass the compensator, scattered photons can be generated within the compensator. These scattered photons affect the head scatter factor for monitor unit calculation. Although many reports related to scattered photons generated within the compensator (60% copper, 40% inc, ρ = 8.37 g cm$^{-3}$). The slab compensator was mounted on a blocking tray at a distance 64.2 cm from the target of the 6-MV linear accelerator (Clinac21EX, Varian, Palo Alto, US). PDD measurement was performed using the automated water phantom system (Blue Phantom, IBA, Schwarzenbruck, Germany) and ionization performed using the automated water phantom system (Blue (Clinac 21EX, Varian, Palo Alto, US). PDD measurement was evaluated. Furthermore, head scatter factor was measured and simulated in order to clarify the effect of scattered photons generated within the compensator.

**MATERIALS AND METHODS**

**Depth dose measurement**

In order to evaluate change of depth dose distribution by the brass compensator, percentage depth doses (PDDs) were measured for several field sizes and thicknesses of brass slab compensator (60% copper, 40% inc, ρ = 8.37 g cm$^{-3}$). The slab compensator was mounted on a blocking tray at a distance of 64.2 cm from the target of the 6-MV linear accelerator (Clinac21EX, Varian, Palo Alto, US). PDD measurement was performed using the automated water phantom system (Blue Phantom, IBA, Schwarzenbruck, Germany) and ionization chamber (CC13, IBA).

**Energy spectrum simulation**

To analyze the photon spectrum varied by the compensator, energy spectra were simulated using the Monte Carlo method. The treatment head was reconstructed on the BEAMnrc simulation code [13–16] with conscientious geometry and material information provided by the manufacturer. Simulation parameters were optimized in order to reproduce actual dose distribution, and reproducibility was confirmed by agreement between measured and simulated dose distributions during the first step of the Monte Carlo procedure [6]. Several thicknesses of slab compensator were mounted on the treatment head and the energy of particles was sampled in the air and in a 10 cm depth of water.

**Beam quality correction factor $k_Q$**

To estimate the variation in ionization chamber sensitivity by beam hardening, the beam quality correction factor, $k_Q$, for four ionization chambers with wall materials consisting of PMMA (TN30013, PTW, Freiburg, Germany), graphite (2505/3,3A, Nuclear Enterprises, Beenham, UK), A-150 (2581, Nuclear Enterprises) and C-552 (PR-06C, Capintec, Ramsey, US) was determined. $k_Q$ is determined by the mean restricted mass collision stopping power ratio of the medium to air $(\bar{L}/\rho)_{\text{m,air}}$ and the overall perturbation factor $P$. $(\bar{L}/\rho)_{\text{m,air}}$ was calculated for several slab compensator thicknesses using the SPRRZnrc code [17–19]. The calculation was performed for water and each chamber wall material. In the calculation, cutoff energy was set at $AE = ECUT = 0.521$ MeV, $AP = PCUT = 0.01$ MeV. $P$ consists of the wall correction factor $P_{\text{wall}}$, scattering differences between the air cavity and the water correction factor $P_{\text{cav}}$, the central electrode correction factor $P_{\text{cel}}$ and the displacement factor $P_{\text{dis}}$. $P_{\text{cav}}$, $P_{\text{cel}}$ and $P_{\text{dis}}$ were determined by the method adopted as the Japanese Society of Medical Physics (JSMP) Standard Dosimetry 01 [20–24]. $P_{\text{wall}}$ was determined by the following equation [25–27]:

$$
(P_{\text{wall}})_{Q} = \alpha \left( \frac{L}{\rho} \right)_{\text{wall,air}} \left( \frac{\bar{\mu}}{\rho} \right)_{\text{w,wall}} \right)
+ \tau \left( \frac{L}{\rho} \right)_{\text{sleeve,air}} \left( \frac{\bar{\mu}}{\rho} \right)_{\text{w,sleeve}} \right)
+ (1 - \alpha - \tau) \left( \frac{L}{\rho} \right)_{\text{w,air}}
$$

Where $\alpha$ and $\tau$ are the ratios of the electrons generated from the chamber wall and the sleeve, respectively. Those values were determined from the experimental value of Lempert et al. [28]. $(\bar{\mu}/\rho)_{\text{w,med}}$ is the mean mass energy absorption coefficient ratio of water to medium and is determined by the following equation:

$$
(\frac{\bar{\mu}}{\rho})_{\text{w,med}} = \frac{\int_{E_{min}}^{E_{max}} \Phi_E E (\mu/\rho)_{\text{w,med}} dE}{\int_{E_{min}}^{E_{max}} \Phi_E E (\mu/\rho)_{\text{med}} dE}
$$

Where $\Phi_E$ is the photon fluence at energy $E$ in water, and the dataset of Seltzer and Hubbell [29, 30] was applied for $(\mu(E)/\rho)$.

**Head scatter factor measurement and scattered photon simulation.**

To evaluate the influence on head scatter factor $S_h$ by scattered photons generated within the compensator, $S_h$ values for several slab compensator thicknesses were determined by measurement of in-air output. Measurement was performed using the Farmer-type ionization chamber (TM30013, PTW, Freiburg, Germany) in combination with
an electrometer (Unidos, PTW). The chamber was positioned at 10 cm depth in the miniphantom, which had a cylindrical shape with a 2-cm radius and was 20 cm in height, and these were placed at SCD = 100 cm on the beam axis. $S_n$ was determined as the ratio of in-air output of an arbitrary field to that of a 10 cm × 10 cm reference field [31].

In order to evaluate the contribution of the scattered photons generated within the compensator to in-air output, influence of primary and scattered photons in air were simulated for several field sizes and compensator thicknesses using the Monte Carlo method. The Monte Carlo simulation parameters were same as in the above section. Scattered photons generated within the compensator were identified by the latch option. The collision water kerma for the arbitrary field $K_{\text{water}}(A)$ was calculated using the following equation:

$$K_{\text{water}}(A) = \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi(E) \frac{\mu_E \rho}{\rho} dE$$

[3]
Where $\Phi_E(A)$ is photon fluence at energy $E$ for field size $A$, and $\mu_{\text{en}}(E)/\rho$ is the mass energy absorption coefficient of water, respectively.

**RESULTS AND DISCUSSION**

**Percentage depth dose**

Figure 1 shows a comparison between the PDD of the open field and that of the compensator field. For a 5-cm compensator and at 10 cm depth, deviations of $\delta$ were 3.3%, 1.7% and 1.1% higher than PDD for $5\,\text{cm} \times 5\,\text{cm}$, $10\,\text{cm} \times 10\,\text{cm}$ and $15\,\text{cm} \times 15\,\text{cm}$ open field, respectively. When X-rays passed the compensator, the depth dose was increased by the beam hardening effect, and this phenomenon is obvious for smaller fields.

Figure 2 shows a comparison of the photon energy spectrum between the open and 5-cm compensator field. In air, the mean photon energy was 1.72 MeV and 2.42 MeV for the $5\,\text{cm} \times 5\,\text{cm}$ field, and 1.68 MeV and 2.21 MeV for the $15\,\text{cm} \times 5\,\text{cm}$ field, respectively. When under the 5-cm compensator, the fluence of low energy photons decreased and mean energy shifted to higher. This result shows beam hardening was obviously taking place in the compensator, but the variation of the energy spectrum by field size was insignificant in air. On the other hand, in water, the mean photon energy was 2.23 MeV and 1.59 MeV for $5\,\text{cm} \times 5\,\text{cm}$ and $15\,\text{cm} \times 15\,\text{cm}$ compensator fields, respectively. For smaller fields, the energy spectrum for the compensator field had no change whether in water or air, and there was an obvious difference between the photon spectrum in water of the open field and the compensator field. However for larger fields, the fluence of low energy photons generated within water was increased and the energy spectrum of compensator field was similar to the open field. This phenomenon explains why variation of PDD was larger for smaller fields.

In order to obtain high accuracy of dose calculation for the compensator IMRT, the energy spectrum should be reproduced correctly.

**Beam quality correction factor $k_Q$**

Figure 3 shows the variation of mean restricted mass collision stopping power ratio of medium to air $(L/\rho)_{\text{m,air}}$ as a function of compensator thickness. As compensator thickness increased, $(L/\rho)_{\text{m,air}}$ decreased in every material. For the 5-cm compensator, the deviation of $(L/\rho)_{\text{water,air}}$ from the open field was 0.5%. This result shows beam hardening may affect beam quality correction factor $k_Q$.

Figure 4 shows the variation of $k_Q$ as a function of compensator thickness. As compensator thickness increased, $k_Q$ for all Farmer-type ionization chambers decreased, and the difference of $k_Q$ between the open and 5-cm compensator fields was 0.45%. Although the $k_Q$ of Farmer-type ionization chamber could be varied because of beam hardening, the variation was in the range of uncertainty of $k_Q$ determination [20, 21].

**Head scatter factor $S_h$**

Variation of $S_h$ for several compensator thicknesses is shown in Fig. 5. When compensator thickness increased, $S_h$ has a steeper gradient. This result shows dose output may be affected by the scattered photons generated within the compensator.

Figure 6 shows the ratio of $\text{col}\,K_{\text{water}}$ of simulated scattered photons generated within the compensator to total scattered photons for several compensator thicknesses. The contribution of the scattered photons generated within the
compensator increases when the field size and compensator thickness increases. Therefore, the scattered photons generated within the compensator should be taken into account in the MU calculation of compensator IMRT.

CONCLUSION

In this report, the influence of a brass compensator on dose calculation and dosimetry was investigated. As a result, when the photon passed the brass compensator, beam hardening occurred, and dose distribution was varied with the compensator. Furthermore, scattered photons were generated within the compensator, and scattered photons affect the head scatter factor. Figure 7 shows the MU calculation difference at 10 cm depth without energy spectrum reproduction and correction of scattered photons for head scatter factor. When the energy spectrum reproduction and correction
of \( S_n \) are not included in the MU calculation, the MU difference is up to 7%. This means that energy spectrum should be reproduced correctly and scattered photons must be taken into account for accurate dose calculation for the brass compensator IMRT. On the other hand, influence of beam hardening on \( k_Q \) was insignificant.

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![Fig. 6. Percentage of collision water kerma of scattered photons from compensator to that of total photons for several compensator thicknesses.](image)

![Fig. 7. MU calculation difference at 10 cm depth without energy spectrum reproduction and correction of scattered photons for head scatter factor.](image)
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