**Original research**

**10-MV X-ray dose calculation in water for MLC and wedge fields using a convolution method with X-ray spectra reconstructed as a function of off-axis distance**

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**Abstract**

**Purpose:** This paper highlights a 10-MV X-ray convolution dose calculation method in water using primary and scatter dose kernels formed for energy bins of X-ray spectra reconstructed as a function of the off-axis distance for a linear accelerator equipped with pairs of upper and lower jaws, a multileaf collimator (MLC) and a wedge filter. **Methods:** The reconstructed X-ray spectra set was composed of 11 energy bins. To estimate the in-air beam intensities at points on the isocenter plane for an MLC field, we employed an MLC leaf-field output subtraction method, using an extended radiation source on each of the X-ray target and the flattening filter as well as simplified two-dimensional plates to simulate the three-dimensional jaws and MLC structures. A special correction factor was introduced for nonuniform incident beam intensities, particularly produced at MLC fields. The in-phantom dose calculation was performed by treating the phantom, the wedge filter, the wedge holder and the MLC as parts of a unified irradiated body, where we proposed to use a special factor for the density scaling theorem within the unified irradiated body. **Conclusions:** The phantom dose was generally separated into nine dose-components: the primary and scatter dose-components produced in the phantom; the primary and scatter dose-components emanating from the wedge, the wedge holder and the MLC; and the electron contamination dose-component. From the calculated and measured percentage depth dose (PDD) and off-center ratio (OCR) datasets, we may conclude that the convolution method can achieve accurate dose calculations even under MLC and/or wedge filtration.

**Keywords:** convolution method; X-ray spectra; dose kernels; wedge; multileaf collimation; MLC leaf-field output subtraction

**Research highlights**

Convolution methods are convenient for three-dimensional (3D) dose calculations, especially for an irregular-beam field with a non-uniform incident-beam intensity distribution. For a convolution method, we performed theoretical and experimental studies on 10-MV X-ray dose calculations in water phantoms with multileaf collimation (MLC) and/or wedge filtration using a linear accelerator equipped with a pair of upper jaws, a pair of lower jaws, an MLC and a wedge filter. The in-phantom dose calculation was performed by treating the phantom, the wedge filter, the wedge holder and the MLC as parts of a unified irradiated body. We can conclude that the convolution method can achieve accurate dose calculations even under MLC and/or wedge filtration.

**Introduction**

Megavoltage X-ray beams from linear accelerators are used for radiation therapy. The X-ray radiation produced in the X-ray target pass through a flattening filter that is symmetric with respect to the isocenter axis. The flattening filter makes the beam intensity distribution relatively uniform across the field. The filter is thickest in the middle.

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and tapers off toward the edges; therefore, the X-ray spectrum is a function of the off-axis distance (radiation softening becomes more pronounced with increasing off-axis distance).

The dose at a point in a medium irradiated by an X-ray beam can be separated into three components. One is the primary dose, arising directly from primary photons that have not interacted with the medium before reaching the point. Another is the dose from scattered radiation originating from all points hit by primary photons in the medium. The last is the contamination dose, caused by electrons from the treatment head and air volume. With model-based algorithms, one can calculate the primary, scatter and contamination dose components separately. Convolution (or superposition) methods are in the class of model-based algorithms. They are convenient for three-dimensional (3D) dose calculations, especially for an irregular-beam field with a nonuniform incident-beam intensity distribution. As reviewed by Ahnesjö and Aspradakis [1], there are two kinds of convolution methods: one is a method that uses pencil-beam kernels, and the other is a method that uses point-dose kernels.

With respect to the latter convolution method, its numerical convolution is also called “the collapsed cone convolution” [2]. The present paper deals with a kind of collapsed cone convolution; however, it is to be emphasized that the dose calculation is performed using multiple primary- and scatter-dose kernels that are formed with the use of X-ray spectra reconstructed [3, 4] as a function of the off-axis distance.

For accurate primary and scatter dose calculations using convolution methods, Iwasaki [5] stipulated that the following four irradiation conditions be met: (a) a nondivergent beam, (b) a homogeneous phantom, (c) a beam attenuation coefficient along ray lines that is not a function of the depth and off-axis distance, and (d) an incident beam intensity that is uniform within the irradiation field and zero outside it. We have not yet dealt with the condition described in (a), Iwasaki, et al. [6] and Kimura, et al. [7] dealt with the condition described in (b) using inhomogeneous phantoms, proposing a correction factor for calculation of the primary dose within thorax-like phantoms, and also dealt with the condition described in (c) using X-ray spectra reconstructed as a function of the off-axis distance. In the present paper, we proposed a special correction factor for nonuniformity of the incident beam intensity described in the above (d) using multileaf collimator (MLC) and/or wedge fields. Because the MLC and wedge devices are usually made of high-Z materials, they can induce large changes in the incident beam intensity (also including the X-ray spectrum changes). The dose calculation simulations are performed using 10-MV X-ray beams, focusing on percentage depth dose (PDD) and off-center ratio (OCR) datasets in water phantoms.

**Materials and methods**

The physical parameters of the materials used in this study were evaluated using data tables published by Hubbell [8]. We used 10-MV X-ray beams from a linear accelerator (CL-2100C; Varian Medical Systems, Palo Alto, CA, USA). The treatment head contains pairs of upper and lower jaws; upper-1, -2 and lower-1, -2 (tungsten alloy) as the jaw collimator which is able to form a jaw field ≤ 40 × 40 cm² on the isocenter plane 100 cm distant from the source (S) (or the X-ray target). The treatment head also features an MLC (Millennium 120 Leaf; Varian Medical Systems) under the jaw-collimator device. Each leaf moves in the same direction as the lower jaws. We used wedge filters supplied by the manufacturer that are designed to be installed directly on the treatment head. The wedge filters, made of steel or lead alloys, form isodose angles of 15°, 30°, 45° and 60° in water and are mounted on an acrylic plate (wedge holder). Figure 1 diagrams the treatment head with an installed wedge. We let $A_{\text{jaw}}$ and $A_{\text{MLC}}$ denote the jaw and MLC fields, respectively, measured on the isocenter plane.

**Symbols and units**

We use the following symbols and units in this paper: the spectra-related energies ($E_i$ and $\Delta E_i$) are expressed in MeV; the normalized set of reconstructed energy fluences ($\psi_i^*(s)$) is expressed in MeV⁻¹; the total in-air beam energy fluence ($\psi_{\text{in},s}^*$) is expressed in J/cm²; the linear attenuation coefficients (e.g., $\mu_{\text{water}}$, $\mu_{\text{air}}$, $\mu_{\text{MLC}}$, $\mu_{\text{med}}$) for media are expressed in cm⁻¹; the lengths ($Z$, $H$, $\xi$, $\eta$, $r$, $R$, $R_o$, etc.) are expressed in cm; the position vectors ($\mathbf{r}$, $\mathbf{r}_o$, $\mathbf{r}_w$, $\mathbf{r}_\text{wedge}$, $\mathbf{r}_\text{MLC}$, $\mathbf{r}_\text{med}$, etc.) are expressed in cm; the primary and scatter dose components ($D_{\text{prim}}$, $D_{\text{scat}}$, etc.) are expressed in Gy; the beam water collision kerma (or the primary water collision kerma) components ($K_{\text{w}, \text{wat}}$, $K_{\text{w}, \text{med}}$, etc.) are expressed in Gy; the dose kernels ($H_{1,2}$, $H_{1,2,\text{w}}$, $H_{\text{w}}$, $H_{\text{med}}$, $H_{\text{MLC}}$, $H_{\text{wedge}}$, $H_{\text{air}}$, $H_{\text{wat}}$, $K_{\text{w}, \text{wat}}$, $K_{\text{w}, \text{med}}$, etc.) are expressed in cm⁻²; the volume element ($\Delta V$) is expressed in cm³; and the area element ($\Delta S$) is expressed in cm².

**Theoretical studies**

We tried to calculate the dose at a point generally in an...
inhomogeneous phantom by treating the phantom, the wedge filter, the wedge holder and the MLC as parts of a unified irradiated body. For this calculation model, we used an orthogonal coordinate system of \((X_{\text{beam}}, Y_{\text{beam}}, Z_{\text{beam}})\) (Figures 1 and 2), setting the origin \((O)\) at the isocenter. We denote the \(Z_{\text{beam}}\) axis as the line connecting the source \((S)\) and the origin \((O)\), coinciding with the isocenter axis, and assume that the \(X_{\text{beam}}\) and \(Y_{\text{beam}}\) axes perpendicularly intersect the upper- and lower-jaw field edges, respectively, on the isocenter plane \((Z_{\text{beam}} = 0 \text{ cm})\), calling this the “beam coordinate system”. The MLC leaves move parallel to the \(Y_{\text{beam}}\) axis, in the same direction as that of the lower jaws. To calculate the expressions of equations 1−3 described in the following text to evaluate the dose at a point \(P(X_v, Y_v, Z_v)\) in the phantom (Figure 2), we use two other coordinate systems in addition to the beam coordinate system \((X_{\text{beam}}, Y_{\text{beam}}, Z_{\text{beam}})\): one is the orthogonal coordinate system \((X_w, Y_w, Z_w)\) with the origin at point \(P\) (it should be noted that the \((X_w, Y_w, Z_w)\) coordinate system just coincides with the \((X_{\text{beam}}, Y_{\text{beam}}, Z_{\text{beam}})\) coordinate system when point \(P\) coincides with the isocenter \((O)\); and the other is the polar coordinate system \((r', \phi, \theta)\) directly associated with the \((X_v, Y_v, Z_v)\) coordinate system.

**Dose calculation principle**

The dose calculation was performed using a convolution method that utilizes special types of in-water primary and scatter dose kernels \(H_{1,2}\) and \(K_{1,2}\) (see Appendix A), formed for the energy bins of X-ray spectra [3, 4] reconstructed as a function of the off-axis distance. It should be noted that the usual number of energy bins is approximately ten, and that the reconstructed X-ray spectra can reasonably be applied [4] to media with a wide range of effective \(Z\) numbers (e.g., from water to lead). When applying the density scaling theorem [9-11] to the in-water primary and scatter dose kernels again under the conditions that the phantom, wedge filter, wedge holder and MLC are treated as parts of a unified irradiated body, the use of the relative electron density \((\rho_e)\) is not feasible. This is because the effective \(Z\) numbers of the media within the unified irradiated body are quite different from one another, depending on the energy bins of the reconstructed X-ray spectra. Thus, we propose to use a factor of \(\frac{\mu_{\text{med}}}{\mu_{\text{water}}}\) (the relative attenuation factor) for the medium of each volume element within the unified irradiated body, where \(\mu_{\text{med}}\) and \(\mu_{\text{water}}\) are the linear attenuation coefficients of the volume element material and water, respectively, and are determined by each of the energy bins of the reconstructed X-ray spectra. For the volume elements existing along a line connecting two points, we propose to use the mean relative electron density \((\bar{\rho}_e)\). It should be noted that the linear attenuation coefficients \(\mu_{\text{med}}, \mu_{\text{water}}\) and \(\mu_{\text{med}}\) generally change with the energy bin of the reconstructed X-ray spectra, whereas \(\rho_e\) or \(\bar{\rho}_e\) does not. In addition, for water-like media, we can assume \(\rho_e = \mu_{\text{med}}/\mu_{\text{water}}\) and \(\bar{\rho}_e = \mu_{\text{med}}/\mu_{\text{water}}\) for any energy bin. This method of using the linear attenuation coefficients may be effective for handling the scatter dose kernels. However, it may not be effective for handling the primary dose kernels because the primary dose is caused by the secondary electrons generated by the interaction between the volume element and the primary photons. The secondary electrons do not have a strong relationship with photon attenuation from the standpoint of energy deposition in media.

![Figure 2](image-url)
Figure 2 also shows a quadrangular pyramid in polar coordinates, whose apex is situated at point \( P \). It shows how to calculate the primary, scatter and electron contamination doses delivered to point \( P \), where the primary and scatter doses arise from the volume elements \( (\Delta V) \) in the unified irradiated body; and the electron contamination dose arises from the area element \( \Delta S \). Regarding to the volume elements \( (\Delta V) \) and area elements \( (\Delta S) \), we employed a series of \( \theta, \phi, \beta, \delta, \gamma \) and \( \Delta r' \) data (see Appendix B). For the convolution dose calculation, (a) we used a set of X-ray spectra reconstructed as a function of the off-axis distance, letting the bin energies be \( E_i (i = 1, 2, \ldots, N_{\text{max}} \), with \( N_{\text{max}} = 10 \) ) for each off-axis distance; (b) we used primary dose kernels \( (P_{\text{water}}, P_{\text{air}}, P_{\text{wedge}}, P_{\text{MLC}}, P_{\text{w_hold}}) \) and scatter dose kernels \( (K_{\text{water}}, K_{\text{air}}, K_{\text{wedge}}, K_{\text{MLC}}, K_{\text{w_hold}}) \) as a function of \( E_i \) for the volume and area elements, where these dose kernels are rebuilt from the in-water primary and scatter dose kernels \( (H_{1,2} \text{ and } K_{1,2}) \); and (c) we estimated values of \( K_{\text{water}} \) and \( K_{\text{water}} \) as a function of \( E_i \) for each of the volume and area elements.

For dose calculation generally under the presence of the MLC and a wedge filter, we divided the dose to point \( P \) into nine components: (a) the primary and scatter doses \( (D_{\text{phan}} \text{ and } D_{\text{phan}}) \) produced in the phantom; (b) the primary and scatter doses \( (D_{\text{phant}} \text{ and } D_{\text{phant}}) \) emanating from the wedge filter; (c) the primary and scatter doses \( (D_{\text{MLC}} \text{ and } D_{\text{MLC}}) \) emanating from the wedge holder; (d) the primary and scatter doses \( (D_{\text{wedge}} \text{ and } D_{\text{wedge}}) \) emanating from the MLC; and (e) the contamination dose \( D_{\text{cont}} \) caused by the electrons emanating from the treatment head and the air volume.

It should be noted that this calculation method does not strictly take into account the primary and scatter doses due to the secondary electrons and scattered photons, respectively, produced in the upper and lower jaws. Instead, it treats the radiation reflected from the jaws as a small increase in the in-air beam intensity using a jaw radiation reflection factor \( [6] \) that lies outside the jaw field, as described by a Monte Carlo simulation model \([12]\) stating that the photons scattered from the jaws can be ignored when estimating the in-air beam intensity within the jaw field.

Within the unified irradiated body, we set the beam water collision kerma \( (K_{\text{watin}} \text{ or } K_{\text{watin}}) \) to emanate from the dose kernel at each \( \Delta V \text{ or } \Delta S \) element point. When the beam water collision kerma should be determined based on the open jaw field without the MLC device, we denote it as \( K_{\text{watin}} \). When the beam water collision kerma should be determined based on the open MLC field under a given jaw field, we denote it as \( K_{\text{watin}} \).

Next, we describe the dose calculation approaches using position vectors, generally taking an irradiation case in which both wedge and MLC devices are installed in a jaw field (Figure 2a). We let \( L \) denote the position vector to a dose calculation point \( P \), drawn from the source \( (S) \); and \( L_{\text{wedge}}, L_{\text{w_hold}} \text{ and } L_{\text{MLC}} \) denote the position vectors to volume elements \( (\Delta V) \) in the phantom, wedge filter, wedge holder and MLC, respectively, drawn from the source \( (S) \). \( L_{\text{w_hold}} \text{ and } L_{\text{MLC}} \) denote the position vector to an area element \( (\Delta S) \) on the phantom surface, drawn from the source \( (S) \). Then the primary, scatter and electron contamination dose calculations are performed using the following approaches.

(a) The primary dose calculation approach:

\[
\begin{align*}
D_{\text{prim}}(L) = & \sum_{i=1}^{N_{\text{max}}} \sum_{s=1}^{5} \left( \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) \right) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{water}}(E_{i}) \Delta V(E_{i}) + \sum_{s=1}^{5} \left( \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) \right) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{water}}(E_{i}) \Delta V(E_{i}) \\
& \sum_{s=1}^{5} \left( \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) \right) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{water}}(E_{i}) \Delta V(E_{i}) + \sum_{s=1}^{5} \left( \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) \right) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{water}}(E_{i}) \Delta V(E_{i}),
\end{align*}
\]

where \( k_{\text{watin}} \) and \( k_{\text{watin}} \) express the beam water collision kermas at the corresponding volume elements \( (\Delta V) \), respectively, in the phantom and in the wedge or MLC device (equations 40-42, 46).

(b) The scatter dose calculation approach:

\[
\begin{align*}
D_{\text{scatter}}(L) = & \sum_{i=1}^{N_{\text{max}}} \sum_{s=1}^{5} \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{scatter}}(E_{i}) \Delta V(E_{i}) + \sum_{i=1}^{N_{\text{max}}} \sum_{s=1}^{5} \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{scatter}}(E_{i}) \Delta V(E_{i}) \\
& \sum_{i=1}^{N_{\text{max}}} \sum_{s=1}^{5} \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{scatter}}(E_{i}) \Delta V(E_{i}) + \sum_{i=1}^{N_{\text{max}}} \sum_{s=1}^{5} \sum_{t=1}^{2} h_{s,t}(L - E_{s,t}; E_{i}) k_{\text{watin}}(L_{\text{watin}}; E_{i}) \mu_{\text{scatter}}(E_{i}) \Delta V(E_{i}),
\end{align*}
\]

(c) The contamination dose calculation approach:

\[
D_{\text{cont}}(L) = \sum_{i=1}^{N_{\text{max}}} \sum_{s=1}^{5} \sum_{t=1}^{2} h_{s,t}(L - L_{\Delta S}; E_{i}) k_{\text{water}}(L_{\Delta S}; E_{i}) \mu_{\text{cont}}(E_{i}) \Delta V(E_{i}) + \sum_{i=1}^{N_{\text{max}}} \sum_{s=1}^{5} \sum_{t=1}^{2} h_{s,t}(L - L_{\Delta S}; E_{i}) k_{\text{water}}(L_{\Delta S}; E_{i}) \mu_{\text{cont}}(E_{i}) \Delta V(E_{i}),
\]

where \( k_{\text{water}} \) expresses the beam water collision kerma at the corresponding phantom surface element \( (\Delta S) \) (equation 43); \( \Delta S \) is defined as the size of the area element on the phantom surface, which faces the source \( (S) \) without interception by the phantom; \( \theta_{\Delta S} \) is the angle between the normal vector line on the \( \Delta S \) surface and the negative vector of \( L_{\Delta S} \); \( G(A_{\text{watin}}) \) expresses the electron contamination factor as a function of the jaw field \( (A_{\text{watin}}) [6, 7] \). \( \Gamma_{1} \) and \( \Gamma_{2} \) are introduced to improve the \( G \) function, which can apply only to open jaw fields and only to electrons streaming along the ray lines emanating from the source \( (S) \).

\( \Gamma_{1} \) represents the degree of attenuation of the contaminant electrons when penetrating the MLC and wedge filter along the position vector \( L_{\Delta S} \). Let \( \Gamma_{1} \) be formulated using
penetration features of the secondary electrons produced by $E_i$ photons as
\[ I_i(T_{w_i}, E_i) = H(T_{w_i}, E_i), \]
where $H(Z, R; E_i)$ expresses the in-water forward primary dose kernel to point $(Z, R)$ produced by $E_i$ photons (refer to Appendix A); and $T_{w_i}(E_i)$ is the total effective thickness for the MLC and wedge devices, evaluated along the position vector $L_{w_i}$ as a function of $E_i$. It is calculated as
\[ T_{w_i}(E_i) = \left[ \mu_{w_{\text{hold}}}(E_i) T_{w_{\text{hold}}} + \mu_{w_{\text{edge}}}(E_i) T_{w_{\text{edge}}} \right] / \mu_{\text{water}}(E_i), \]
where $\mu_{w_{\text{hold}}}(E_i)$, $\mu_{w_{\text{edge}}}(E_i)$, $\mu_{w_{\text{hold}}}(E_i)$ and $\mu_{w_{\text{edge}}}(E_i)$ are the linear attenuation coefficients of the MLC, wedge filter, wedge holder and water, respectively, for $E_i$ photons; and $T_{w_{\text{MLC}}}$, $T_{w_{\text{edge}}}$ and $T_{w_{\text{hold}}}$ are the thicknesses of the MLC, wedge filter and wedge holder, respectively, measured along the position vector $L_{w_i}$.

$\Gamma_2$ is introduced to improve the accuracy of the calculation at points very near the phantom surface [7], to take into account the dose delivered by the contaminant electrons coming across the ray lines. For phantoms constructed of water-like media, we express $\Gamma_2$ as
\[ \tilde{\mu}_{\text{med}}(E_i) / \mu_{\text{water}}(E_i) \]
and $H_{\text{phan}}(Z, R; E_i)$ is evaluated along the line connecting $P$ and the center of $\Delta S$, where $\tilde{\mu}_{\text{med}}(E_i)$ is evaluated along the line connecting $P$ and the effective point within the $\Delta V$ element; and $F_{\text{phan}}$ is a correction factor [6, 7] for phantom heterogeneity. This correction factor is simply used only for forward primary dose calculations, not as a function of $E_i$. We should set $F_{\text{phan}} = 1$ for homogeneous phantoms.

Next, we examine the dose kernels of $h_{\text{phan}}$, $h_{\text{wedge}}$, $h_{w_{\text{hold}}}$, $h_{\text{MLC}}$, $h_{\text{phan}}$, $h_{\text{wedge}}$ and $h_{w_{\text{hold}}}$ (equations 1-3) used in the unified irradiated body. According to the aforementioned density scaling theorem, the coordinates of $\xi$, $\eta$, $r$, $\xi_s$, $\eta_s$ and $r_s$ shown in Figure 3 can be converted to the in-water coordinates as:
\[ \xi = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \xi_i, \eta = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \eta_i, \]
\[ \xi_s = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \xi_{\text{s}}. \]

Then, the dose kernels in equations 1-3 can be evaluated by employing the in-water dose kernels as follows (also refer to the angles of $\theta_{\text{phan}}$, $\theta_i$, $\theta_{\text{wedge}}$, $\theta_{w_{\text{hold}}}$ and $\theta_{\text{MLC}}$ in Figure 2):

(a) $h_{\text{phan}}$ in equation 1 is one of the following two kernels:
\[ h_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \cdot \left[ H_{\text{phan}}(Z, R; E_i) \right] \cdot \left[ F_{\text{phan}} \right] \cdot \left[ F_{\text{derm}} \right], \] for $\theta_{\text{phan}} \leq \pi/2$ (7)
\[ h_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \cdot \left[ H_{\text{phan}}(Z, R; E_i) \right] \cdot \left[ F_{\text{phan}} \right] \cdot \left[ F_{\text{derm}} \right], \] for $\theta_{\text{phan}} > \pi/2$ (8)

where $\tilde{\mu}_{\text{med}}(E_i)$ is evaluated along the line connecting $P$ and the effective point within the $\Delta V$ element; and $F_{\text{phan}}$ is a correction factor [6, 7] for phantom heterogeneity. This correction factor is simply used only for forward primary dose calculations, not as a function of $E_i$. We should set $F_{\text{phan}} = 1$ for homogeneous phantoms.

(b) $k_{\text{phan}}$ in equation 2 is one of the following two kernels:
\[ k_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)}, \] for $\theta_{\text{phan}} \leq \pi/2$ (9)
\[ k_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)}, \] for $\theta_{\text{phan}} > \pi/2$ (10)

(c) $h_{\text{phan}}$ in equation 3 is one of the following two kernels:
\[ h_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \cdot \left[ H_{\text{phan}}(Z, R; E_i) \right] \cdot \left[ F_{\text{phan}} \right] \cdot \left[ F_{\text{derm}} \right] \cdot \left[ F_{\text{wedge}} \right], \] for $\theta_{\text{phan}} \leq \pi/2$ (11)
\[ h_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \cdot \left[ H_{\text{phan}}(Z, R; E_i) \right] \cdot \left[ F_{\text{phan}} \right] \cdot \left[ F_{\text{derm}} \right] \cdot \left[ F_{\text{wedge}} \right], \] for $\theta_{\text{phan}} > \pi/2$ (12)

\[ k_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \cdot \left[ H_{\text{phan}}(Z, R; E_i) \right] \cdot \left[ F_{\text{phan}} \right] \cdot \left[ F_{\text{derm}} \right] \cdot \left[ F_{\text{wedge}} \right] \cdot \left[ F_{\text{wedge}} \right], \] for $\theta_{\text{phan}} \leq \pi/2$ (13)
\[ k_{\text{phan}}(\xi, \eta; E_i) = \frac{\tilde{\mu}_{\text{med}}(E_i)}{\mu_{\text{water}}(E_i)} \cdot \left[ H_{\text{phan}}(Z, R; E_i) \right] \cdot \left[ F_{\text{phan}} \right] \cdot \left[ F_{\text{derm}} \right] \cdot \left[ F_{\text{wedge}} \right] \cdot \left[ F_{\text{wedge}} \right], \] for $\theta_{\text{phan}} > \pi/2$ (14)

where $F_{\text{wedge}}$ and $F_{\text{wedge}}$ are the correction factors, respectively, for the calculation of the primary and scatter dose components, not as a function of $E_i$. We express them as
\[ F_{\text{wedge}} = \alpha_{\text{wedge}} \cdot T_{\text{wedge}} \cdot \beta_{\text{wedge}} \cdot \gamma_{\text{wedge}} \cdot \delta_{\text{wedge}}, \] (15)
\[ F_{\text{wedge}} = 1 / \left( 1 + \alpha_{\text{wedge}} \cdot T_{\text{wedge}} \cdot \beta_{\text{wedge}} \cdot \gamma_{\text{wedge}} \cdot \delta_{\text{wedge}} \right), \] (16)
with \( T_{\text{wedge}} = \sqrt{\frac{2}{\alpha} + R^2} \), where \( a_{\text{wedge, p}} = 2.5 \times 10^{-2}, \beta_{\text{wedge, p}} = 0.5, a_{\text{wedge, s}} = 7.0 \times 10^{-6}, \beta_{\text{wedge, s}} = 0.5 \) and \( y_{\text{wedge, s}} = 50 \) for each of the 15°, 30°, 45° and 60° wedges (wedge types 1–4) (these values, without units, were derived by comparing the calculated and measured dose datasets).

(e) \( h_{\text{w, hold}} \) and \( k_{\text{w, hold}} \) (used as \( \theta_{\text{w, hold}} < \pi/2 \)) in equations 1 and 2 are, respectively,

\[
h_{\text{w, hold}}(\xi, r; E_n) = \left( \frac{\mu_{\text{w, hold}}(E_n)}{\mu_{\text{water}}(E_n)} \right)^2 \cdot h_{\text{1}} \left( \xi, r; E_n \right) \cdot F_{\text{w, wedge, p}} \cdot F_{\text{w, wedge, s}}, \tag{17}
\]

\[
k_{\text{w, hold}}(\xi, r; E_n) = \left( \frac{\mu_{\text{w, hold}}(E_n)}{\mu_{\text{water}}(E_n)} \right)^2 \cdot k_{\text{1}} \left( \xi, r; E_n \right) \cdot F_{\text{w, wedge, s}}, \tag{18}
\]

(f) \( h_{\text{MLC}} \) and \( k_{\text{MLC}} \) (used as \( \theta_{\text{MLC}} < \pi/2 \)) in equations 1 and 2 are, respectively,

\[
h_{\text{MLC}}(\xi, r; E_n) = \left( \frac{\mu_{\text{MLC}}(E_n)}{\mu_{\text{water}}(E_n)} \right)^2 \cdot h_{\text{1}} \left( \xi, r; E_n \right) \cdot F_{\text{MLC, p}}, \tag{19}
\]

\[
k_{\text{MLC}}(\xi, r; E_n) = \left( \frac{\mu_{\text{MLC}}(E_n)}{\mu_{\text{water}}(E_n)} \right)^2 \cdot k_{\text{1}} \left( \xi, r; E_n \right) \cdot F_{\text{MLC, s}}, \tag{20}
\]

where \( F_{\text{MLC, p}} \) and \( F_{\text{MLC, s}} \) are the correction factors, respectively, for the calculation of the primary and scatter dose components emanating from the MLC, not as functions of \( E_n \). We express them as

\[
F_{\text{MLC, p}} = a_{\text{MLC, p}} \cdot T_{\text{MLC, p}}, \tag{21}
\]

\[
F_{\text{MLC, s}} = 1 \left( \frac{1 + a_{\text{MLC, s}} \cdot T_{\text{MLC, s}}}{1 + a_{\text{MLC, s}} \cdot T_{\text{MLC, s}}} \right), \tag{22}
\]

with \( T_{\text{MLC}} = \sqrt{\frac{2}{\alpha} + R^2} \), where we let

\[
a_{\text{MLC, p}} = 1 \times 10^{-3}, a_{\text{MLC, s}} = 1.5, a_{\text{MLC, s}} = 100, T_{\text{MLC, s}} = 1.5 \text{ and } T_{\text{MLC, s}} = 1.0
\]

(these values without units were derived by comparing the calculated and measured dose datasets).

Modeling the jaw collimator, MLC and wedge devices

The jaw collimator, MLC and wedge devices are 3D objects (Figure 4a). However, to simplify the calculation of the in-air beam intensity with an open jaw field or with an open MLC field under a jaw field, and to also simplify the calculation of the dose that the phantom receives from the MLC and wedge, we treated the jaws, MLC and wedge as two-dimensional (2D) structures. That is, we treated them as plates with no geometrical thickness (Figure 4b). The following describes the details of the jaws, MLC and wedge plates:

(a) The jaw collimator is simulated by four plates that are perpendicular to the isocenter axis. They are located at four positions: \( Z_{\text{beam}} = Z_{\text{upper,1}} = 72.0 \text{ cm}, \ Z_{\text{beam}} = Z_{\text{upper,2}} = 72.0 \text{ cm}, \ Z_{\text{beam}} = Z_{\text{lower,1}} = 63.3 \text{ cm} \) and \( Z_{\text{beam}} = Z_{\text{lower,2}} = 63.3 \text{ cm} \). The \( Z_{\text{upper,1}} \) and \( Z_{\text{upper,2}} \) positions coincide with the corresponding top edges of the upper-1 and -2 jaws, respectively, and the \( Z_{\text{lower,1}} \) and \( Z_{\text{lower,2}} \) positions coincide with the corresponding top edges of the lower-1 and -2 jaws, respectively. We assume that these four plates form the same irradiation field on the isocenter plane as the real jaws do, and that the radiation emanating from the source (S) is perfectly shielded by the plates. This replacement is performed [6] to calculate in a simple manner the in-air beam intensity caused by the extended radiation source.
on the X-ray target plane and the extended radiation source on the flattening-filter plane. It should be noted that this replacement causes a slight inconvenience for the calculation of the in-air beam intensity outside the jaw field (refer to the circle mark in Figure 5b as described later).

(b) The MLC is simulated by a plate perpendicular to the isocenter axis at the position \( Z_{\text{beam}} = Z_{\text{MLC}} (= 53.7 \text{ cm}, \) which was determined by analyzing the measured MLC-S_\text{S} datasets shown in Figure 6 below). We let the plate form the same MLC field as the MLC does on the isocenter plane, corresponding to the MLC effective thicknesses along ray lines emanating from the source \( S \). This dataset is used to calculate the in-air beam intensity for the open MLC field. It is also used for calculating the dose that the phantom receives from the MLC.

(c) Each of the wedges (15°, 30°, 45° and 60°) and their 0.2 cm acrylic holder are replaced with a plate perpendicular to the isocenter axis at the fixed position \( Z_{\text{beam}} = Z_{\text{wedge}} (= 42.4 \text{ cm}) \), which is the same as the position of the boundary surface of the wedge and its holder. We let the plate form the wedge field as the wedge device does on the isocenter plane, corresponding to the wedge filter and wedge holder thicknesses along ray lines emanating from the source \( S \). This dataset is used to calculate the dose that the phantom receives from the wedge device and the in-air beam intensity under the wedge-filtered jaw or MLC field.

\[ Q_{\text{in-air}} = Q_{\text{open}} - A_{\text{MLC}} - A_{\text{wedge}} \]

In-air output factor calculation for open MLC fields

We describe how to calculate the in-air beam intensity for an open MLC field under a given jaw field (without wedge filtration). The calculation is based on the MLC leaf-field output subtraction method [16] at the 15° ICRU. The details are; Zhu and Bjärngard [17] and Zhu and colleagues [18-20] introduced the 2D Gaussian-source model for the extended radiation source only with a flattening filter to calculate the in-air output factor \( (S) \) [21, 22] for open jaw or MLC fields. Later, Iwasaki and colleagues [6] proposed the use of this model not only for the flattening filter but also for the X-ray target (or the source \( S \)). It was found that using the two extended radiation sources was effective, even around a zero-area jaw field under conditions of lateral electron disequilibrium. We propose using the two extended radiation sources model to calculate the in-air output factor \( (O \text{P} F_{\text{in-air}}) \) for an open MLC field under a given jaw field by subtracting the in-air output reduction caused by setting the MLC field to the jaw field from the in-air output for the open jaw field (let the in-air output reduction be designated the negative or “black” in-air output). This calculation method can take into account the delicate in-air output variations caused by the MLC leaf curvature and chamfers at the leaf end and the MLC interleaf X-ray leakage.

Figure 5 shows the calculation of the \( O \text{P} F_{\text{in-air}} \) factor at a point \( Q(x_0, y_0) \) on the isocenter plane for an open MLC field \( (A_{\text{MLC}}) \) under a given jaw field \( (A_{\text{jaw}}) \), where Figures 5a, b are drawn for the cases where point \( Q \) is inside and outside the \( A_{\text{jaw}} \) field, respectively. An extended radiation source exists around point \( Q_1 \) (coinciding with the center of the X-ray target) on the source plate; and another extended radiation source is assumed to exist around point \( Q_2 \) at the intersection of the flattening-filter plate and the ray line connecting points \( Q_1 \) and \( Q \). On the isocenter plane, we introduce a special field called a black MLC field \( (A_{\text{MLC}}) \).
which is to evaluate the amount of negative (or black) in-air output, where the dashed lines in Figures 5a, b are drawn by taking into account the positions of the lower jaw plates (in like manner, another set of dashed lines should also be utilized by taking into account the positions of the upper jaw plates). It should be emphasized that, if point Q is outside the A jaw field, the A field does not contain point Q. In this case, as indicated by the circle mark in Figure 5b, the A field extends beyond the A jaw field edge. Such an extended region is caused by the treatment

\[
\text{OPF}_{\text{in-air}}(X_o, Y_o; A_{\text{MLC}}, A_{\text{jaw}}) = \left[ \frac{H_{\text{jaw}}(X_o, Y_o; A_{\text{jaw}})}{H_{\text{MLC}}(0,0; 10 \times 10_{\text{cm}})} - \frac{H_{\text{black}}(X_o, Y_o; A_{\text{MLC}})}{H_{\text{MLC}}(0,0; 10 \times 10_{\text{cm}})} \right] \cdot \text{OCR}_{\text{source}}(R) \cdot \text{RRF}_{\text{jaw}}(X_o, Y_o),
\]

with \( R_0 = \sqrt{X_0^2 + Y_0^2} \), where OCRsource\((R_0)\) is the source off-center ratio [6], obtained by assuming that it is a function of only for an open infinite A jaw field (defined as the in-air beam intensity (in water collision kerma) at a point that is \( R_0 \) distant from the isocenter that is at the isocenter (that is, OCRsource\((0) = 1\)). where the OCRsource dataset was produced by applying an in-air chamber response function [4] of \( y(R_0) = \exp(0.002R_0 - 0.00002R_0^2) \) to an in-air dose dataset measured only at points of \( y_{\text{beam}} \geq 0 \) on the \( y_{\text{beam}} \) axis). RRF_{\text{jaw}} is the jaw-collimator radiation reflection factor [6], letting RRF_{\text{jaw}} = 1 and RRF_{\text{jaw}} > 1, respectively, inside and outside the A jaw field. For beams with no MLC device, we obtain \( H_{\text{black}} = 0 \) by setting AMLC = \( \infty \) (infinite field) and AMLC in equation 23 (see Appendix C for definitions of “off-center jaw-S factor”, “MLC-S factor” and “jaw-S factor”).

First, we formulate [6] \( H_{\text{jaw}} \) in equation 23 as

\[
H_{\text{jaw}}(X_o, Y_o; A_{\text{jaw}}) = \frac{1}{\pi(\lambda_1/2)^2} \int_{a_1}^{\lambda_1} \exp\left[-R_o^2 / (\lambda_1/2)^2\right] d\lambda_1,
\]

where \( C_{\text{jaw}} \) is the side of the equivalent square field for A jaw and \( a_1, a_2, \lambda_1, \) and \( \lambda_2 \) are constants, where it is assumed that \( a_1 \) (the monitor-backscatter coefficient) is influenced only by the jaw collar, which forms the A jaw field, and not by the MLC or by the wedge. For the present 10-MV X-ray accelerator, we have obtained \( a_1 = 0.00146 \text{cm}^{-1}, a_2 = 0.0830, \lambda_1 = 0.299 \text{ cm}, \) and \( \lambda_2 = 3.097 \text{ cm}. \) It can be understood that \( H_{\text{jaw}} \) approaches zero as the A jaw field approaches zero.

Next, we formulate [16] \( H_{\text{black}} \) in equation 23 as

\[
H_{\text{black}}(X_o, Y_o; A_{\text{MLC}}) = \frac{1}{\pi(\lambda_1/2)^2} \int_{a_1}^{\lambda_1} \exp\left[-R_o^2 / (\lambda_1/2)^2\right] d\lambda_1,
\]

where point \( (X_{MLC}, Y_{MLC}) \) should be within the AMLC region (Figure 5a, b show how point Q, area element dA\(_S\) (or dA\(_L\)) point \( Q_0 \) and point \( (X_{MLC}^S, Y_{MLC}^S) \) are related); and \( Y_{MLC} \) is the of the 2D jaw-collimator plates (the irradiation geometry tells us that, if the real 3D jaw collimator can be utilized, no such large A field can be generated).

We normalize the OPF_{in-air} factor to unity at the isocenter with an open jaw field of \( A_{\text{jaw}} = 10 \times 10 \text{ cm}^2 \), whose center coincides with the isocenter. Then, the OPF_{in-air} factor at point \( Q(X_o, Y_o) \) for an open AMLC field under a given A jaw field can be calculated as

\[
\text{OPF}_{\text{in-air}}(X_o, Y_o; A_{\text{MLC}}, A_{\text{jaw}}) = \left[ \frac{H_{\text{jaw}}(X_o, Y_o; A_{\text{jaw}})}{H_{\text{MLC}}(0,0; 10 \times 10_{\text{cm}})} - \frac{H_{\text{black}}(X_o, Y_o; A_{\text{MLC}})}{H_{\text{MLC}}(0,0; 10 \times 10_{\text{cm}})} \right] \cdot \text{OCR}_{\text{source}}(R) \cdot \text{RRF}_{\text{jaw}}(X_o, Y_o),
\]

with \( \text{MLC} = \sqrt{X_{MLC}^2 + Y_{MLC}^2} \) and \( \text{MLC} \) in equation 23, normalized set of energy fluence spectra (Ψ(\( E, \text{MLC} \))) expresses the energy fluence spectrum for an open infinite jaw field, as a function of the energy bin \( E_{\text{jaw}} \) and the off-axis distance (\( R_{\text{jaw}} \)) (Figure 7), normalized as

\[
\frac{\sum_{N=1}^{\infty} \Psi(E_{\text{jaw}}, R_{\text{jaw}})}{\Delta E_{\text{jaw}}} = 1.
\]
The total in-air energy fluence

For an open infinite jaw field yielding an in-air water collision kerma of $OCR_{\text{source}}(R_0)$ on the isocenter plane (equation 23), the total in-air energy fluence ($\Psi_{\text{total}}(x, y)$) at a point $(x, y)$ can be evaluated as

$$\Psi_{\text{total}}(x, y) = \frac{OCR_{\text{source}}(R_0)}{\rho} \sum_{n=1}^{N} \left( \mu_n(E_{\text{air}}) \right) \Psi(E_{\text{air}}, R_0) \Delta E_n,$$

with $R_0 = \sqrt{X_0^2 + Y_0^2}$. It should be noted that the denominator of equation 31 expresses the total water collision kerma that the normalized energy fluence spectrum yields at the corresponding point in air. Therefore, the in-air energy fluence related to the normalized energy fluence of $\Psi(E_n, R_0)$ $\Delta E_n$ yields the following in-air water collision kerma:

$$K_{\text{water}}^{\text{in-air}}(x, y) = \frac{\mu_n(E_{\text{air}})}{\rho} \Psi(E_{\text{air}}, R_0) \Delta E_n. \quad (32)$$

The in-phantom dose calculations described below are carried out using the $K_{\text{water}}^{\text{in-air}}$ function. If a wedge filters the open jaw or MLC field, we calculate the in-air water collision kerma variation for each set of primary photons ($N = 1$ to $N_{\text{max}}$), depending on the wedge thickness along the corresponding ray line. This is because the in-phantom dose is calculated by using the primary photons emitted from the source $(S)$ and by treating the phantom, the wedge and the MLC as parts of a unified irradiation body.

**Calculation of $K_{\text{water}}^{\text{in-air}}$ and $K_{\text{MLC}}^{\text{in-air}}$**

This section is described mainly by referring to figures 4, 5, 8, and 9, where the 2D wedge and MLC plates are placed at $Z_{\text{beam}} = Z_{\text{wedge}}$ and $Z_{\text{beam}} = Z_{\text{MLC}}$ respectively. We set up the preconditions that the 2D wedge and MLC plates hold data regarding the thicknesses (or effective thicknesses) of the 3D wedge and the MLC devices, respectively, measured along the ray lines emanating from the source $(S)$. In the inserted diagram on the right in Figure 8, we let $T_0$ denote the thickness (or effective thickness) measured along a ray line passing through a point $(X'_0, Y'_0, Z'_0)$ on the wedge or MLC plate and through a point $Q(X_0, Y_0)$ on the isocenter plane, and let $\phi$ denote the angle between the ray line and the isocenter plane. Then the thickness (or effective thickness) along the line that is parallel to the $Z_{\text{beam}}$ axis and passes through the point $(X'_0, Y'_0, Z'_0)$ is approximated as $T_0 \sin \phi$. Draw an arc $r'$ from a dose calculation point $P(X_0, Y_0, Z_0)$ that passes through the point $(X'_0, Y'_0, Z'_0)$. Then the thickness (or effective thickness) measured along the $r'$ axis can be approximated as $T_0 \sin \phi / \sin \phi$, where $\phi$ is the angle between the $r'$ axis and the isocenter plane. On the basis of this procedure, the following describes how to handle the 3D wedge and MLC devices.

First, we refer to the thickness (or effective thickness) measured from the bottom side along the $r'$ axis using the symbol $U'$ ($L = 1$ to $L_{\text{max}}$). The diagram shows the case when $L_{\text{max}} = 5$ with equal interval sections $\Delta L_0$ and a residual section $\Delta L_0 + \Delta L_0$ along a line parallel to the $Z_{\text{beam}}$ axis. We estimate the value for $U'$ as

$$U' = (T_0 - T'_0) \sin \phi / \sin \phi,$$

with

$$\Delta \phi = 5 \text{ with equal interval sections } \Delta L_0,$$
at point \( P \) and parallel to the \( Z_{\text{beam axis}} \) and the \( r' \) axis. Then the magnitude of \( \Delta V' \) is given as
\[
\Delta V' = \frac{\Delta A_e \Delta L_e}{\cos \theta_0}, \quad (l = 1, 2, \cdots, L_{\text{max}} - 1),
\]
(37)
\[
\Delta V'_{\text{ref}} = \frac{\Delta A_0 \Delta L_e}{\cos \theta_0},
\]
(38)
where \( \Delta A_0 = a_1' \left[ \cos (\theta - \Delta \theta / 2) - \cos (\theta + \Delta \theta / 2) \right] \Delta \phi \).

To calculate the primary and scatter doses from the wedge and MLC bodies, we used \( \Delta L_e = 0.01 \) cm and \( \Delta L_e = 0.1 \) cm, respectively. To calculate both the primary and scatter doses from the wedge holder, we used \( \Delta L_e = 0.2 \) cm (that is, \( L_{\text{max}} = 1 \) in Figure 8). The value of \( T_0 \) measured along each ray line was obtained by analyzing the manufacturer’s diagrams. However, we assumed that each of the MLC leaves had no driving screw holes (0.33 cm and 0.43 cm in diameter for the 0.5 cm and 1 cm wide leaves, respectively).

Next, we describe the calculation of the beam water collision kerma of \( K_{\text{water}} \) and \( K_{\text{water}}' \) (equations 1-3) for a given volume element \( \Delta V' \) or \( \Delta V \) or \( \Delta V' \) or \( \Delta V'_{\text{ref}} \) within the unified irradiated body (Figure 8). Because the X-ray emission from the flattening filter is very small relative to that from the X-ray target (for the present 10-MV X-ray accelerator, the strength ratio of the extra radiation source to the X-ray target for an infinite \( A_{\text{fw}} \) field is \( \alpha_2 = 0.0830 \) (equation 24), we assumed that all X-rays emanate from the source (S).

It has been found that, particularly under MLC field irradiation, the \( \text{OPF}_{\text{in-air}} \) factor (equation 23) determined on the basis of a single point within each \( \Delta V' \) element in the phantom cannot give accurate dose calculation results. This is mainly caused by the nonuniformity of the beam intensities within each \( \Delta V' \) element owing to the use of the MLC. In the following dose calculation procedures, the symbol \( \text{OPF}_{\text{in-air}} \) is used when the beam intensity for each \( \Delta V' \) element in the phantom should be evaluated based on the beam intensity at a single point within each \( \Delta V' \) element. On the other hand, the symbol \( \text{OPF}_{\text{in-air}} \) is used when the in-air beam intensity for each \( \Delta V' \) element in the phantom should be evaluated based on the beam intensities at multiple points within each \( \Delta V' \) element (the details will be described later in equation 47).

Here we classify the wedge irradiation mode using wedge types = 0 to 4, stipulating that wedge type = 0 signifies irradiation with no wedge (that is, open jaw or MLC field irradiations), and wedge types 1, 2, 3 and 4 denote jaw or MLC field irradiations with the use of a 15°, 30°, 45° and 60° wedge, respectively. Under these conditions, the following (a)-(e) describe the evaluation of the beam intensity for a point \((X_0', Y_0', Z_0')\) (\( l = 1 \) to \( L_{\text{max}} \)) within the MLC or wedge, or for a point \((X_0, Y_0, Z_0)\) on the phantom surface or within the phantom (Figure 8), these points are on a ray line passing through point \( Q(X_0, Y_0) \) on the isocenter plane).

(a) For the beam intensity calculation within the MLC device, we set \( Z_0' = Z_{\text{MLC}} (\approx 53.7 \) cm), which is determined by analyzing calculated and measured MLC-S-S datasets (Figure 6). The \( K_{\text{water}}' \) collision kerma caused by the \( E_h \) photons for the \( \Delta V' \) element at the point \( (X_0', Y_0', Z_{\text{MLC}}) \) in the \( l^{\text{th}} \) section of the MLC plate should be evaluated only under a given \( A_{\text{fw}} \) opening, because the MLC device is placed in close proximity to the jaw collimator; that is, an MLC field of \( A_{\text{MLC}} = \infty \) should be used to evaluate \( \text{OPF}_{\text{in-air}} \) in the following equation. Therefore, the calculation is performed as follows:
\[
k_{\text{water}}' \left( X_0', Y_0', Z_{\text{MLC}} \right) = -\psi(\theta_0, \xi_0) \rho_{\text{MLC}} \mu_{\text{water}} \left( X_0, Y_0, Z_{\text{MLC}} \right),
\]
where \( \text{SAD} = 100 \) cm is the source-axis distance (or the distance between the source (S) and the isocenter plane);
\( T_{\text{MLC}} \left( X_0', Y_0' \right) \) is the effective thickness of the MLC, measured along the corresponding ray line (Figure 8) from the MLC top side to the middle point \((X_0', Y_0', Z_{\text{MLC}})\) of the \( l^{\text{th}} \) section; and \( \mu_{\text{MLC}}(E_h) \) is the linear attenuation coefficient of the MLC material for \( E_h \) photons.

(b) For the beam intensity calculation within the wedge holder, we set \( Z_0' = Z_{\text{wedge}} (\approx 42.4 \) cm) with \( l = 1 \) (\( l = L_{\text{max}} \) Figure 8). The \( K_{\text{water}}' \) collision kerma caused by the \( E_h \) photons for the \( \Delta V' \) element at the point \( (X_0', Y_0', Z_{\text{wedge}}) \) in the \( l^{\text{th}} \) section of the wedge holder should also be evaluated only under a given \( A_{\text{fw}} \) opening (that is, an MLC field of \( A_{\text{MLC}} = \infty \) should be used for \( \text{OPF}_{\text{in-air}} \) in the following equation). Therefore, the calculation is performed as follows:
\[
k_{\text{water}}' \left( X_0', Y_0', Z_{\text{wedge}} \right) = -\psi(\theta_0, \xi_0) \rho_{\text{wedge}} \mu_{\text{water}} \left( X_0, Y_0, Z_{\text{wedge}} \right),
\]
where \( \text{SAD} = 100 \) cm is the source-axis distance (or the distance between the source (S) and the isocenter plane);
\( T_{\text{wedge}} \left( X_0', Y_0' \right) \) is the wedge-holder thickness (equation 35) measured along the corresponding ray line, from the wedge-holder top side to the middle point \((X_0', Y_0', Z_{\text{wedge}})\) of the \( l^{\text{th}} \) section; and \( \mu_{\text{wedge}}(E_h) \) is the linear attenuation coefficient of the wedge-holder material for \( E_h \) photons. For the case of no MLC in the beam, we should set \( T_{\text{MLC}}(X_0, Y_0) = 0 \).

(c) For the beam intensity calculation within the wedge body, we set \( Z_0' = Z_{\text{wedge}} (\approx 42.4 \) cm) with \( l = 1, 2, \cdots, L_{\text{max}} \) (Figure 8). The \( K_{\text{water}}' \) collision kerma caused by the \( E_h \) photons for the element at the point \((X_0', Y_0', Z_{\text{wedge}}) \) in the \( l^{\text{th}} \) section of the wedge body should also be evaluated only under a given \( A_{\text{fw}} \) opening (that is, \( A_{\text{MLC}} = \infty \) should be used for \( \text{OPF}_{\text{in-air}} \) in the following equation). Therefore, the calculation is performed as follows:
\[
k_{\text{water}}' \left( X_0', Y_0', Z_{\text{wedge}} \right) = -\psi(\theta_0, \xi_0) \rho_{\text{wedge}} \mu_{\text{water}} \left( X_0, Y_0, Z_{\text{wedge}} \right),
\]
where \( \text{SAD} = 100 \) cm is the source-axis distance (or the distance between the source (S) and the isocenter plane); \( T_{\text{wedge}} \left( X_0', Y_0' \right) \) is the wedge-body thickness (equations 34 and 35) measured along the corresponding ray line, from the wedge-body top side to the middle point \((X_0', Y_0', Z_{\text{wedge}})\) of the \( l^{\text{th}} \) section; and \( \mu_{\text{wedge}}(E_h) \) is the linear attenuation coefficient of the wedge-body material for \( E_h \) photons. For the case of no MLC in the beam, we should set \( T_{\text{MLC}}(X_0, Y_0) = 0 \).
(d) For the beam intensity calculation for the ∆S element at the point (X0, Y0, Z0) on the phantom surface, we should take into account the AMLC field under a given Ajaw opening. Under the condition that the wedge generally covers the beam, we let the AMLC collision kerma for ∆S caused by E0 photons be calculated as follows:

\[
K_{\text{water}}^{\text{MLC}}(X_0, Y_0, Z_0, F_0) = \Psi^{\text{Maw}}(X_0, Y_0) \cdot \text{OPF}_{\text{water}}^{\text{MLC}} \cdot [C_{\text{jaw}}^{\text{MLC}} / A_{\text{jaw}} + \text{wedge type}] \cdot \left( T_{\text{MLC}}(X_0, Y_0) \cdot \Delta S^{\text{MLC}} / A_{\text{jaw}} \right)^{0.5} \cdot \exp \left[ -\mu_{\text{water}}(F_0) \cdot T_{\text{water}}(X_0, Y_0) + \mu_{\text{wedge}}(F_0) \cdot T_{\text{wedge}}(X_0, Y_0) \right],
\]

where \( \Delta S^{\text{MLC}} \) is the field area that the MLCC collimator forms inside the A jaw field on the isocenter plane (that is, \( 0 \leq \Delta S^{\text{MLC}} / A_{\text{jaw}} \leq 1 \)); \( T_{\text{MLC}}(X_0, Y_0) \) is the effective thickness of the MLC, measured along the corresponding ray line (note that, for any ray line within the MLC field, we should set \( T_{\text{MLC}}(X_0, Y_0) = 0 \)); \( C_{\text{jaw}}^{\text{MLC}} \) is a factor introduced to make a small correction for the beam intensity calculation by employing OPF_{water}^{\text{MLC}}, given as a function of both \( A_{\text{MLC}}^{\text{jaw}} / A_{\text{jaw}} \) and the wedge type (Appendix D); \( C_{\text{OPF}}^{\text{MLC}} \) is a factor introduced to correct for the beam intensity calculation, given as a function of \( T_{\text{MLC}}(X_0, Y_0) \) and \( A_{\text{MLC}}^{\text{jaw}} / A_{\text{jaw}} \) finely adjusting the degree of X-ray penetration when passing through the MLC effective thickness of \( T_{\text{MLC}}(X_0, Y_0) \) along the corresponding ray line; and \( T_{\text{water}}(X_0, Y_0) \) and \( T_{\text{wedge}}(X_0, Y_0) \) are the thicknesses of the wedge holder and the wedge body, respectively, measured along the ray line (for the case of no wedge device in the beam, we should set \( T_{\text{wedge}}(X_0, Y_0) = T_{\text{wedge}}(X_0, Y_0) = 0 \).

(e) To calculate the beam intensity for the ∆V element at the point (X0, Y0, Z0) within the phantom, we should also take into account the AMLC field under a given A jaw opening. Here, it should be noted that the ray line passing through the point (X0, Y0) on the isocenter plane should also pass through the effective point (Figure 2b) within the ∆V element. It has been found that the same \( C_{\text{OPF}}^{\text{MLC}} \) and \( C_{\text{OPF}}^{\text{MLC}} \) factors as before should be used to make small corrections also for the beam intensity calculation by employing OPF_{water}^{\text{MLC}}. Assuming that the wedge generally covers the beam, we let the AMLC collision kerma for ∆V caused by the E0 photons be calculated as follows:

\[
K_{\text{water}}^{\text{MLC}}(X_0, Y_0, Z_0, F_0) = \Psi^{\text{Maw}}(X_0, Y_0) \cdot \text{OPF}_{\text{water}}^{\text{MLC}} \cdot [C_{\text{jaw}}^{\text{MLC}} / A_{\text{jaw}} + \text{wedge type}] \cdot \left( T_{\text{MLC}}(X_0, Y_0) \cdot \Delta S^{\text{MLC}} / A_{\text{jaw}} \right)^{0.5} \cdot \exp \left[ -\mu_{\text{water}}(F_0) \cdot T_{\text{water}}(X_0, Y_0) + \mu_{\text{wedge}}(F_0) \cdot T_{\text{wedge}}(X_0, Y_0) \right],
\]

where, assuming that the phantom is constructed of water-equivalent media, \( T_{\text{water}}(X_0, Y_0) \) is the effective thickness of the phantom, measured along the ray line from the phantom surface to the point \((X_0, Y_0, Z_0)\) and \( \mu_{\text{water}}(E_0) \) is the linear attenuation coefficient of water for the E0 photons.

For the case of no wedge device in the beam, we should set \( T_{\text{wedge}}(X_0, Y_0) = T_{\text{wedge}}(X_0, Y_0) = 0 \). The OPF_{water}^{\text{MLC}} factor is experimentally constructed as

\[
\text{OPF}_{\text{water}}^{\text{MLC}} \left( X_0, Y_0, A_{\text{MLC}}, A_{\text{jaw}}, \text{wedge type} \right) = \text{OPF} \cdot \exp \left[ -\lambda_{\text{OPF}} \left( A_{\text{MLC}}^{\text{jaw}} / A_{\text{jaw}} ; \text{wedge type} \right) W_{\text{off}} \right],
\]

with

\[
\lambda_{\text{OPF}} \left( A_{\text{MLC}}^{\text{jaw}} / A_{\text{jaw}} ; \text{wedge type} \right) = \lambda_{\text{wedge}} \left( \text{wedge type} \right) \cdot [1 - A_{\text{MLC}}^{\text{jaw}} / A_{\text{jaw}}]
\]

and

\[
\text{OPF} = \sum_{j=1}^{N} \frac{\text{OPF}_j}{J_{\text{max}}}
\]

where \( \lambda_{\text{opt}} = 1.25 \) (no units) for the irradiation mode of wedge type = 0 (that is, for open jaw and MLC fields), and \( \lambda_{\text{opt}} = 3.50 \) for the irradiation modes of wedge type = 1-4 (that is, for wedge-filtered jaw and MLC fields). These \( \lambda_{\text{opt}} \) values were obtained by comparing the calculated and measured percentage depth dose (PDD) and off-center ratio (OCR) datasets. This paper uses \( J_{\text{max}} = 27 \) as the number of multiple points set within each ∆V element, through which ray lines of \( j = 1, 2, ..., J_{\text{max}} \) pass (nine points on each of the three planes set perpendicular to the r’ axis (Figure 2b); and OPF is the OPF_{water}^{\text{MLC}} factor (equation 23) at the point where the r’ ray line intersects the isocenter plane (Figure 2b). We have \( \lambda_{\text{OPF}} = 0 \) for \( A_{\text{MLC}}^{\text{jaw}} / A_{\text{jaw}} = 1 \) for any wedge type. \( W_{\text{off}} \) expresses the degree of nonuniformity of the incident beam intensity for a given ∆V element, determined by \( A_{\text{MLC}}^{\text{jaw}} \) and \( A_{\text{MLC}} \) and wedge type. It should be noted that, in equation 47, we generally have \( \text{OPF}_{\text{water}}^{\text{MLC}} \leq \text{OPF} \). It has been found that the work of the \( \text{OPF}_{\text{water}}^{\text{MLC}} \) factor becomes remarkable as the width of an MLC leaf-blocked section in a jaw field becomes narrow (Figures 10 and 11).

**Spectra and dose kernels**

We reconstructed [3, 4] a new set of energy fluence spectra for the accelerator as follows. We measured sets of in-air transmission data at points on the Ybeam axis where \( Y_{\text{beam}} \geq 0 \) using an ionization chamber with an acrylic buildup cap (a factor of \( f_{\text{cap}} = 0.25 \) was assumed [4] to account for radiation attenuation and scatter in the buildup cap), in which we used acrylic attenuators of 0-30 cm in thickness and lead attenuators of 0-3 cm in thickness at off-axis distances of \( R_0 = 0, 2.5, 5.0, 7.5, 10.0, 12.5, 15.5, 17.5 \) and 19.5 cm. We set a value of 10.329 MV for the accelerating voltage. Using a common set of energy bins for all the off-axis distances, we reconstructed a set of \( \Psi(E_0, R_0) \) spectra with an accuracy of approximately ±1% for the measured transmission data. The energy bins were \( E_1 = 0.167 \text{ (} E_{\text{min}}, E_2 = 0.627, E_3 = 1.087, E_4 = 1.548, E_5 = 2.008, E_6 = 2.468, E_7 = 3.461, E_8 = 4.987, E_9 = 6.513, E_{10} = 8.040 \text{ and } E_{11} = 9.566 \text{ MeV (} E_{\text{max}} \text{) (namely, } N_{\text{max}} = 11 \text{ and } E_{\text{max}} = 2.698 \text{ MeV with } \Delta E = 0.460 \text{ MeV for } N = 1-6, \text{ and with } \Delta E = 1.526 \text{ MeV for } N = 7-11). Figure 7 shows the reconstructed spectra at \( R_0 = 0-19.5 \text{ cm.} \) The X-ray spectrum becomes softer as the off-axis distance (\( R_0 \)) increases.
Figure 10 Graphs of the OCR\textsubscript{calc} (including its components) and OCR\textsubscript{meas} (in points) datasets, with the $X_{\text{beam}}$ value varied with $Y_{\text{beam}} = 0$ cm on the isocenter plane at a reference depth of $Z_{R} = 5$ cm with no wedge used, founded by setting (a) one half-leaf (0.5 cm in width), (b) three consecutive half-leaves (1.5 cm in width) and (c) five consecutive half-leaves (2.5 cm in width) in a jaw field of $A_{\text{jaw}} = 10 \times 10 \text{ cm}^2$. 10-MV X-rays, SAD = 100 cm (each reference dose was obtained at $Z_{R} = 5$ cm using the open $A_{\text{jaw}}$ field).

$H_{1,2}$ and $K_{1,2}$ dose kernels
Primary and scatter dose kernels in water ($H_{1,2}$ and $K_{1,2}$) for the energy bins of $E_{p}$ ($N = 1$ to 11) were produced through use of an Electron Gamma Shower (EGS) Monte Carlo code taking semi-infinite water phantoms (Figure A1). The primary and scatter dose kernels (as shown in Kimura and colleagues [7]) were produced, assuming the density of water to be unity.

Structure of the MLC
The MLC is made of a proprietary tungsten alloy.
plane (Figure 4). On the whole, these numerical values gave the most accurate results for the MLC-$S_c$ factor.

The MLC device is composed of sixty pairs of leaves. Let $N_{\text{leaf}}$ denote the leaf number. At $N_{\text{leaf}} = 1$ and $N_{\text{leaf}} = 60$, each of the leaves forms a special shadow field 1.4 cm wide on the isocenter plane. At $N_{\text{leaf}} = 2-10$ and $N_{\text{leaf}} = 51-59$, each of the leaves forms a shadow field 1 cm wide, called a “full leaf” or “type 0.” At $N_{\text{leaf}} = 11-50$ forms a shadow field 0.5 cm wide, called a “half leaf.” The half leaves are classified into two types, type 1 and type 2, and these types are arrayed alternately. The full and half leaves have [23] a staple, a hook, a curved end, stepped sides and chamfers at both corners of the curved end so that these leaves can be moved to create an irregular field shape.

We analyzed the fine 3D structure of the full and half leaves as per the manufacturer’s information. When the full and half leaves are consecutively arrayed, the isocenter-axis components of the MLC effective thicknesses calculated along the ray lines are separated into seven or eight sections, respectively, in the direction of the $X_{\text{beam}}$-axis (excluding the region around each curved end and ignoring the presence of the driving screw holes). Figure 12 illustrates the sectional widths measured on the isocenter plane for leaves of (a) type 0 (full), (b) type 1 (half) and (c) type 2 (half). The width of the region overlapped with the neighboring leaf is 0.067 cm; accordingly, each type has an actual width of 0.567 or 1.067 cm. The data in brackets give the isocenter-axis components. Figure 13 illustrates the 3D shapes of the isocenter-axis components for a single full or half leaf: (a) full leaf (type 0; using $N_{\text{leaf}} = 10$), (b) half leaf (type 1; using $N_{\text{leaf}} = 30$) and (c) half leaf (type 2; using $N_{\text{leaf}} = 31$). Note that the diagrams are drawn by setting the position of each leaf end at $Y_{\text{beam}} = 0$ cm.

**MLC-$S_c$ calculation**

Using equation 23, we calculated the in-air output factor (OPF$_{\text{in_air}}$) under a given set of $A_{\text{MLC}}$ and $A_{\text{jaw}}$ fields along each center line of the seven or eight stripes using its sectional width (Figure 12) for each of the full or half MLC leaves. However, for $N_{\text{leaf}} = 1$ and 60 we assumed that each leaf had an infinite width, repeating the eight-striped pattern of the full leaf (to take into account the overrun area, as indicated by the circle in Figure 5b, when the $X_{\text{beam}}$-axis side edge of the $A_{\text{jaw}}$ field is nearly equal to ±20 cm). Moreover, to effectively calculate near the leaf end, we used a series of $\Delta T_{\text{leaf}}$ steps on the middle line of each stripe, starting at the leaf end, as follows:

$$\Delta T_{\text{leaf}} = \frac{1}{2} \left( 1 - \cos \left( i \right) \right) \left( 1 - \exp \left( - \frac{\ln 2}{\Delta T_{\text{max}}} \right) \right) \Delta T_{\text{min}} \Delta T_{\text{step}} \Delta T_{\text{in_air}},$$

for $i = 1, 2, 3, \ldots$, where we let $T_{\text{leaf}} = 0$ cm and $T_{\text{leaf}} = \Delta T_{\text{leaf}}$ (the step increases slowly at small and large values of $i$). For the experimental studies, we used $\Delta T_{\text{leaf}} = 0.01$ cm, $\Delta T_{\text{max}}$ = 0.5 cm and $T_{\text{leaf}} = 1.0187$ cm.

Figure 6 shows the calculated and measured MLC-$S_c$ datasets that were obtained at the isocenter ($X_0 = Y_0 = 0$ cm) as a function of the square $A_{\text{MLC}}$ field size under each of the square $A_{\text{jaw}}$ fields of $6 \times 6$ to $28 \times 28$ cm$^2$ in size (equation C2 in Appendix C), letting both $A_{\text{MLC}}$ and $A_{\text{jaw}}$ fields be symmetric with respect to the $X_{\text{beam}}$ and $Y_{\text{beam}}$ axes, and letting the other pairs of A and B MLC leaves be closed at $Y_{\text{beam}} = 0$ cm. The measurement was performed using a cylindrical mini-phantom [24] with a 0.6 cm$^3$ chamber (PTW 30006 Waterproof Farmer Chamber, Radiation Products Design, Inc. Albertville, MN, USA) in free air. It can be seen that the measurement, having small waveforms for each of the
The 3D shapes of the isocenter-axis components of the MLC effective thicknesses calculated along ray lines, as a function of $X_{\text{beam}}$ and $Y_{\text{beam}}$, for a single full or half leaf whose leaf end point is at $Y_{\text{beam}} = 0$ cm (ignoring the presence of the driving screw hole): (a) for the full leaf (type 0; using $N_{\text{leaf}} = 10$), (b) for the half leaf (type 1; using $N_{\text{leaf}} = 30$) and (c) for the half leaf (type 2; using $N_{\text{leaf}} = 31$).

Structure of the wedge filters

The 15° and 30° wedge filters are made of proprietary iron alloys, and the 45° and 60° wedge filters are made of proprietary lead alloys. Accordingly, to effectively calculate the wedge-filtered dose, we introduced a factor, called $\rho_{\text{wedge}\_\text{factor}}$, giving the ratio of the mass density of the wedge material to that of pure iron or lead (assuming, to a first approximation, that the wedge material is composed of iron or lead, though its density is different from the density of pure iron or lead) for each of the four wedges. We set $\rho_{\text{wedge}\_\text{factor}} = 0.900$ for the 15° wedge; $\rho_{\text{wedge}\_\text{factor}} = 0.915$ for the 30° wedge; $\rho_{\text{wedge}\_\text{factor}} = 0.955$ for the 45° wedge; and $\rho_{\text{wedge}\_\text{factor}} = 0.930$ for the 60° wedge. These factors were obtained by comparing calculated and measured PDD and OCR datasets.

Each wedge body is attached to a 0.2 cm thick acrylic plate. Figure 14 shows cross-sectional body views of the wedges. The vertical axis shows the isocenter-axis components of the wedge thickness measured along ray lines, as a function of $X_{\text{beam}}$ or $Y_{\text{beam}}$ on the isocenter plane. Each view forms a polygonal structure with corners marked by dots.

Calculation of PDD and OCR

The dose calculations in water phantoms described below were performed by setting the density of water to 0.990 g/cm³ to obtain the most accurate calculation results (this value is approximately 0.65% less than that at room temperature). We calculated the dose at a point $P(x_C, y_C, z_C)$ in a water phantom, using a polar coordinate system $(r', \phi, \theta)$ derived from the $(x_v, y_v, z_v)$ coordinate system (Figure 2). Using the procedures described in Appendix B for setting steps of $(\Delta r', \Delta \phi, \Delta \theta)$ and for setting the effective point for each volume element $\Delta V$ on the $r'$-axis, the dose calculation ability was assessed with PDD and OCR datasets that were measured in water phantoms using a 0.125 cm³ ionization chamber (dimension of sensitive volume: radius 2.75 mm, length 6.5 mm; PTW 31002, Radiation Products Design, Inc.), setting the effective center of the chamber to coincide with each measuring point.

Setting the source–surface distance (SSD) to be 100 cm (equal to the source–axis distance (SAD)), we let the PDD be defined along the isocenter axis ($X_{\text{beam}} = Y_{\text{beam}} = 0$ cm) as: $A_{\text{MLC}}$. The mean absolute deviation of the calculations is 0.21% (the minimum is -0.71% and the maximum is 0.68%). The MLC-$S_{\text{c}}$ factor depends largely on the $A_{\text{MLC}}$ field; however, under a given $A_{\text{MLC}}$ field, the MLC-$S_{\text{c}}$ factor rapidly decreases from a certain $A_{\text{MLC}}$ field size as the $A_{\text{MLC}}$ field becomes smaller. It should be noted that, when the positions of the pairs of closed leaves are set at $Y_{\text{beam}} = \pm 30$ cm, the mean absolute deviation of the calculations is 0.22% (the minimum is -0.77% and the maximum is 0.67%). Therefore, it is clear that the in-air output factor (OPF$_{\text{in\_air}}$) is influenced by the shapes of the MLC leaf structures. This is because the value of $A_{\text{MLC}}$ calculated by setting the positions of the closed leaves at $Y_{\text{beam}} = Y_{\text{beam}} = \pm 30$ cm is greater than that calculated with $Y_{\text{beam}} = 0$ cm.
where $D_1$ in the numerator is the dose at a phantom at depth $Z$ on the isocenter axis for an MLC field ($A_{MLC}$) under a jaw field ($A_{jaw}$) with no wedge used (wedge type = 0) or with one of the four wedges (wedge type = 1-4, also indicating its insertion direction); and $D_2$ in the denominator is the reference dose at a phantom at a reference depth of $Z_R = 10$ cm on the isocenter axis under a reference jaw field ($A_{jaw}$) with no MLC (namely, $A_{MLC} = \infty$, an infinite field) and with no wedge (wedge type = 0), where the symbol $D_R^k$ is used below as the reference dose.

Next, setting the source–chamber distance (SCD) to be 100 cm (= SAD), we let the OCR be defined at a point $(X_{beam}, Y_{beam})$ on the isocenter plane ($Z_{beam} = 0$ cm) as:

$$OCR(X_{beam}, Y_{beam}) = D_1(X_{beam}, Y_{beam}; A_{MLC}, A_{jaw}, Z_{R}; \text{wedge type}) / D_2(0, 0; A_{MLC}^h, A_{jaw}^h, Z_{R}; \text{wedge type}) \quad (\text{52})$$

where $D_1$ in the numerator is the dose at a point $(X_{beam}, Y_{beam})$ on the isocenter plane at a reference depth of $Z_R$ on the isocenter axis for an MLC field ($A_{MLC}$) under a jaw field ($A_{jaw}$) with no wedge filter (wedge type = 0) or with one of the four wedges (wedge type = 1-4) also indicating its insertion direction; and $D_2$ in the denominator is the reference dose at the isocenter point on the isocenter plane at the reference depth ($Z_R$) under a reference jaw field of $A_{jaw}^h = A_{jaw}$ with no MLC (namely, $A_{MLC}^h = \infty$ and with no wedge (wedge type = 0), where the symbol $D_R^k$ is used below as the reference dose.

According to the section of Dose calculation principle, each of $D_i$ and $D_j$ in equations 52 and 53 is typically composed of the nine dose components ($D_{\text{prim}}$, $D_{\text{scat}}$, $D_{\text{scat}}$, $D_{\text{prim}}$, $D_{\text{cont}}$, $D_{\text{cont}}$) or the three dose components ($D_{\text{prim}}$, $D_{\text{scat}}$, and $D_{\text{cont}}$).

Experimental studies and discussion

The PDD and OCR datasets in the water phantoms were calculated and measured, where the square $A_{MLC}$ and $A_{jaw}$ fields used below were all symmetric with respect to the $X_{beam}$ and $Y_{beam}$ axes. It should be noted that, for any given square field, the MLC leaves not taking part in forming the open $A_{MLC}$ field were intentionally closed at $Y_{beam} = 0$ cm, and that each of the measured PDD or OCR datasets (drawn in dots in the figures below), producing the ratio of the dose relative to the reference dose, had a relative error of approximately ±0.7% because each measurement of $D_1$ and $D_2$ at a fixed point had a relative error of approximately ±0.5%.

PDD datasets

The calculated and measured PDD ($PDD_{calc}$ and $PDD_{meas}$) datasets, given as a function of the depth ($Z$) of a phantom on the isocenter axis under each irradiation condition, are shown below. Let the $PDD_{calc}$ components corresponding to the nine dose components mentioned above be expressed as:
large deviations were produced), although the calculation results at depths beyond the buildup region are relatively poor (Figure 16a shows deviations = -28.2% (\( Z = 0.008 \) cm) to 6.8% (\( Z = 0.8 \) cm), and Figure 16c shows deviations = -80.7% (\( Z = 0.008 \) cm) to 8.2% (\( Z = 0.8 \) cm); this paper does not analyze further why such large deviations were produced; and (d) \( \text{PDD}_{\text{calc}} = 0 \) and \( \text{PDD}_{\text{core}} = 0 \) at depths greater than approximately 5.8 cm. Results with almost the same calculation accuracy were also obtained for the other combinations of \( A_{\text{MLC}} \) and \( A_{\text{jaw}} \) fields.

Second, PDD(\( Z \)) datasets using the 15°, 30°, 45° and 60° wedges in the direction of the \( \gamma_{\text{beam}} \) axis were calculated and measured for combinations of square \( A_{\text{MLC}} \) and \( A_{\text{jaw}} \) fields as follows: we set \( A_{\text{MLC}} = 4 \times 4 - 10 \times 10 \) cm² for a jaw field of \( A_{\text{jaw}} = 10 \times 10 \) cm²; we set \( A_{\text{MLC}} = 4 \times 4 - 15 \times 15 \) cm² for a jaw field of \( A_{\text{jaw}} = 15 \times 15 \) cm²; and we set \( A_{\text{MLC}} = 4 \times 4 - 20 \times 20 \) cm² for a jaw field of \( A_{\text{jaw}} = 20 \times 20 \) cm². Figures 15a-c show the PDD_{calc} (including its components) and PDD_{meas} datasets: diagram (a) is for a combination of \( A_{\text{MLC}} = 4 \times 4 \) cm² and \( A_{\text{jaw}} = 10 \times 10 \) cm² (details of the lower dose components are shown in diagram (b)); and diagram (c) is for a combination of \( A_{\text{MLC}} = 8 \times 8 \) cm² and \( A_{\text{jaw}} = 10 \times 10 \) cm² fields. It can be seen that (a) each of the primary and scatter doses from the MLC can be ignored; (b) the electron contamination dose decreases as the \( A_{\text{MLC}} \) field decreases for a given \( A_{\text{jaw}} \) field; and (c) the calculated data at depths greater than around 20 cm are approximately 1–2% greater than the corresponding measured data (this paper does not analyze further why such large deviations were produced); and (d) \( \text{PDD}_{\text{calc}} = 0 \) and \( \text{PDD}_{\text{core}} = 0 \) at depths greater than approximately 5.8 cm. Results with almost the same calculation accuracy were also obtained for the other combinations of \( A_{\text{MLC}} \) and \( A_{\text{jaw}} \) fields.

large deviations were produced), although the calculation results at depths beyond the buildup region are relatively poor (Figure 16a shows deviations = -28.2% (\( Z = 0.008 \) cm) to 6.8% (\( Z = 0.8 \) cm), and Figure 16c shows deviations = -80.7% (\( Z = 0.008 \) cm) to 8.2% (\( Z = 0.8 \) cm); this paper does not analyze further why such
OCR datasets

This section presents details of the calculated and measured OCR (OCR\textsubscript{calc} and OCR\textsubscript{meas}) datasets, with the \(Y\text{\textsubscript{beam}}\) value varied and \(X\text{\textsubscript{beam}}\) kept constant, or with the \(X\text{\textsubscript{beam}}\) value varied and \(Y\text{\textsubscript{beam}}\) kept constant, on the isocenter plane at the reference depth (\(Z_0\)) under each irradiation condition.

Let the OCR\textsubscript{calc} components corresponding to the nine dose components mentioned above be expressed as:

\[
\begin{align*}
\text{OCR}_{\text{calc}}^{\text{prim}} &= D_{\text{calc}}^{\text{prim}} / D_0^2; \quad \text{OCR}_{\text{calc}}^{\text{scat}} = D_{\text{calc}}^{\text{scat}} / D_0^2; \\
\text{OCR}_{\text{wedge}}^{\text{prim}} &= D_{\text{wedge}}^{\text{prim}} / D_0^2; \quad \text{OCR}_{\text{wedge}}^{\text{scat}} = D_{\text{wedge}}^{\text{scat}} / D_0^2; \\
\text{OCR}_{\text{MLC}}^{\text{prim}} &= D_{\text{MLC}}^{\text{prim}} / D_0^2; \quad \text{OCR}_{\text{MLC}}^{\text{scat}} = D_{\text{MLC}}^{\text{scat}} / D_0^2;
\end{align*}
\]

Then we have:

\[
\text{OCR}_{\text{calc}} = \text{OCR}_{\text{calc}}^{\text{prim}} + \text{OCR}_{\text{calc}}^{\text{scat}} + \text{OCR}_{\text{wedge}}^{\text{prim}} + \text{OCR}_{\text{wedge}}^{\text{scat}} + \text{OCR}_{\text{MLC}}^{\text{prim}} + \text{OCR}_{\text{MLC}}^{\text{scat}} + \text{OCR}_{\text{cont}}
\]

First, we calculated and measured the OCR(\(X\text{\textsubscript{beam}}, Y\text{\textsubscript{beam}}\)) datasets, with the \(Y\text{\textsubscript{beam}}\) value varied and \(X\text{\textsubscript{beam}} = 0\) cm on the isocenter plane at a reference depth of \(Z_0 = 10\) cm, setting each of the four wedges in the direction of the \(Y\text{\textsubscript{beam}}\) axis and with no MLC (\(A\text{\textsubscript{MLC}} = \infty\)). When using the 15°, 30° and 45° wedges, we set square jaw fields of \(A\text{\textsubscript{jaw}} = 5 \times 5 - 15 \times 15\) cm\(^2\). When using the 60° wedge, we set square jaw fields of \(A\text{\textsubscript{jaw}} = 5 \times 5 - 15 \times 15\) cm\(^2\). Figures 17a-e show the OCR\textsubscript{calc} (including its components) and OCR\textsubscript{meas} datasets for a jaw field of \(A\text{\textsubscript{jaw}} = 15 \times 15\) cm\(^2\): diagram (a) is for the 15° wedge (details of the lower dose components are shown in diagram (b)); diagram (c) is for the 30° wedge; diagram (d) is for the 45° wedge; and diagram (e) is for the 60° wedge. We obtain \(\text{OCR}_{\text{calc}}^{\text{scat}} \equiv 1 \times 10^{-3}\) and \(\text{OCR}_{\text{calc}}^{\text{wedge}} \equiv 5 \times 10^{-4}\) at points around \(Y\text{\textsubscript{beam}} = 0\) cm. For all the calculation points, we obtain \(\text{OCR}_{\text{cont}} = 0\), \(\text{OCR}_{\text{wedge}}^{\text{prim}} = 0\) and \(\text{OCR}_{\text{wedge}}^{\text{scat}} = 0\) (because the contaminant electrons and the secondary electrons from the wedge device are all shielded by the wedge and the 10 cm of water). In general, both the OCR\textsubscript{calc} and OCR\textsubscript{meas} datasets were in good agreement (with deviations of -0.03 to 0.09% at points around \(Y\text{\textsubscript{beam}} = 0\) cm, except in the case of Figure 17d with a relatively large deviation of -1.5% at points around \(Y\text{\textsubscript{beam}} = 0\) cm (this paper does not analyze further why such large deviations were produced). Results with almost the same calculation accuracy were also obtained for the other OCR datasets.

Next, we calculated and measured the OCR(\(X\text{\textsubscript{beam}}, Y\text{\textsubscript{beam}}\)) datasets with the \(X\text{\textsubscript{beam}}\) value varied and \(Y\text{\textsubscript{beam}} = 0\) cm on the isocenter plane at each reference depth of \(Z_0 = 2.5, 5\) and 10 cm with no wedge used by setting each of the following three MLC leaf-blocked sections within a jaw field of \(A\text{\textsubscript{MLC}} = 10 \times 10\) cm\(^2\). Figures 10a-c show the OCR\textsubscript{calc} (including its components) and OCR\textsubscript{meas} datasets for \(Z_0 = 5 \times 5 - 15 \times 15\) cm\(^2\). Figures 17a-e show the OCR\textsubscript{calc} (including its components) and OCR\textsubscript{meas} datasets for \(Z_0 = 5 \times 5 - 15 \times 15\) cm\(^2\) with the use of MLC leaf-blocked sections: diagram (a) is for one half-leaf (0.5 cm in width); diagram (b) is for three consecutive half-leaves (1.5 cm in width); and diagram (c) is for five consecutive half-leaves (2.5 cm in width). For all the calculation points, we obtained \(\text{OCR}_{\text{cont}} = 0\), \(\text{OCR}_{\text{wedge}}^{\text{prim}} = 0\) and \(\text{OCR}_{\text{wedge}}^{\text{scat}} = 0\) (because the contaminant electrons are practically shielded by the wedge). It can be seen that the OCR\textsubscript{meas} data behind the MLC leaf-blocked section by the one half-leaf (Figure 10a) are slightly greater (2.5%) than the OCR\textsubscript{calc} data because the chamber readings are somewhat influenced by higher doses in the non-leaf-blocked regions, and that, in the non-leaf-blocked regions, the OCR\textsubscript{calc} data are around 2% greater than the OCR\textsubscript{meas} data (these large deviations may be due to the assumption that OCR\textsubscript{source} is a function of only the off-axis distance (\(R_0\)); in fact, the basic OCR\textsubscript{source} dataset was produced based only on in-air dose data measured at points where \(Y\text{\textsubscript{beam}} \geq 0\) on the \(Y\text{\textsubscript{beam}}\) axis). Almost the same calculation accuracy was also observed for the other datasets. It should be emphasized that the work of the \(\text{OPF}_{\text{hull}}\) factor (equation 47) becomes

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure16.png}
\caption{Graphs of the PDD\textsubscript{calc} (including its components) and PDD\textsubscript{meas} (in points) datasets for \(A\text{\textsubscript{MLC}} = 5 \times 5\) cm\(^2\) and \(A\text{\textsubscript{jaw}} = 15 \times 15\) cm\(^2\) with the use of (a) a 15° wedge (details of the lower dose region are shown in (b)); and (c) a 60° wedge (each in the direction of the \(Y\text{\textsubscript{beam}}\) axis). 10-MV X-rays, SSD = 100 cm (each reference dose was obtained at \(Z_0 = 10\) cm using the open \(A\text{\textsubscript{MLC}}\) field).}
\end{figure}
remarkable as the width of an MLC leaf-blocked section in a jaw field becomes narrow. The same statement can also be referred to the cases of Figures 11a-c described in the next place.

Next, we calculated and measured the OCR($X_{\text{beam}}$, $Y_{\text{beam}}$) datasets with the $Y_{\text{beam}}$ value varied and $X_{\text{beam}} = 1.75$ cm on the isocenter plane at each reference depth of $Z_R = 2.5$, 5 and 10 cm with no wedge used by setting each of the following three MLC leaf-blocked sections in a jaw field of $A_{\text{jaw}} = 10 \times 10$ cm$^2$. Figures 11a-c show the OCR$_{\text{calc}}$ (including its components) and OCR$_{\text{meas}}$ datasets for $X_{\text{beam}} = 1.75$ cm and $Z_R = 10$ cm: diagram (a) is for one half-leaf (0.5 cm); diagram (b) is for three consecutive half-leaves (1.5 cm); and diagram (c) is for five consecutive half-leaves (2.5 cm). For all the calculation points, we obtained OCR$_{\text{cont}} = 0$ (because the contaminant electrons are practically all shielded by the 10 cm of water), and also obtained OCR$_{\text{MLC}} = 0$ and OCR$_{\text{MLC}} = 0$. The OCR$_{\text{meas}}$ data behind the MLC leaf-blocked section by the one half-leaf (Figure 11a) are slightly greater (3.5%) than the OCR$_{\text{calc}}$ data because the chamber readings are also influenced by higher doses in the non-leaf-blocked regions. In Figure 11b, the OCR$_{\text{calc}}$ data in the non-leaf-blocked region are around 2% greater than the OCR$_{\text{meas}}$ data (this paper does not analyze further why such large deviations were produced). Figure 11a-c reveal that certain amounts of radiation leak at points which are behind the MLC leaf-blocked sections but within the jaw field. Results with almost the same calculation accuracy were also observed for the other datasets.

Next, we calculated and measured the OCR($X_{\text{beam}}$, $Y_{\text{beam}}$) datasets, with the $Y_{\text{beam}}$ value varied and $X_{\text{beam}} = 0, 1.25$ and...
3.75 cm on the isocenter plane at each reference depth of $Z = 2.5, 5$ and 10 cm with the use of each of the four wedges in the direction of $Y_{\text{beam}}$ axis. For each of the 15°, 30° and 45° wedges, we set an MLC field of $A_{\text{MLC}} = 5 \times 5 \text{ cm}^2$ for the jaw fields of $A_{\text{jaw}} = 10 \times 10, 15 \times 15$ and $20 \times 20 \text{ cm}^2$. For the use of the 60° wedge, we set an MLC field of $A_{\text{MLC}} = 5 \times 5 \text{ cm}^2$ for the jaw fields of $A_{\text{jaw}} = 10 \times 10$ and $15 \times 15 \text{ cm}^2$. Figures 18a-e show the OCR$_{\text{calc}}$ (including its components) and OCR$_{\text{meas}}$ datasets for $X_{\text{beam}} = 0 \text{ cm}$ and $Z_R = 10 \text{ cm}$ with a combination of $A_{\text{MLC}} = 5 \times 5 \text{ cm}^2$ and $A_{\text{jaw}} = 15 \times 15 \text{ cm}^2$ fields: diagram (a) is for the 15° wedge (details of the lower dose region are shown in diagram (b)); diagram (c) is for the 30° wedge; diagram (d) is for the 45° wedge; and diagram (e) is for the 60° wedge. For all the calculation points, we obtained OCR$_{\text{calc}} = 0$, OCR$_{\text{meas}} = 0$ OCR$_{\text{wedge}} = 0$ and OCR$_{\text{wedge \_ hold}} = 0$ (because the contaminant electrons and the secondary electrons from the MLC and wedge devices cannot reach each of the calculation points), and also obtained OCR$_{\text{wedge \_ hold}} = 0$ and OCR$_{\text{wedge \_ hold}} = 0$. We obtained OCR$_{\text{wedge \_ hold}} = 3 \times 10^{-5}$ - $8 \times 10^{-5}$ at points around $Y_{\text{beam}} = 0 \text{ cm}$. Figures 18a, c-e show that the deviations of the OCR$_{\text{calc}}$ data at $Y_{\text{beam}} = 0 \text{ cm}$ are -0.8%, -1.8%, -1.1% and -1.8%, respectively (these deviations may be caused by the inaccurate estimates of $\rho_{\text{wedge \_ factor}}$ given for the wedges under the given OCR$_{\text{source}}$ distribution), and that certain amounts of X-rays leak at points which are outside the MLC field but within the jaw field. Similar results were also observed in other irradiation cases, as described below. Results with almost the same calculation accuracy were also obtained for the other OCR datasets.

Next, we calculated and measured the OCR($X_{\text{beam}}, Y_{\text{beam}}$) datasets, with the $Y_{\text{beam}}$ value varied and $X_{\text{beam}} = 0 \text{ cm}$ on the isocenter plane at a reference depth of $Z = 10 \text{ cm}$, for $A_{\text{MLC}} = 5 \times 5 \text{ cm}^2$ and $A_{\text{jaw}} = 15 \times 15 \text{ cm}^2$ with the use of (a) a 15° wedge, (b) details of the lower dose region, (c) a 30° wedge, (d) a 45° wedge and (e) a 60° wedge (each in the direction of the $Y_{\text{beam}}$ axis). 10-MV X-rays, SAD = 100 cm (each reference dose was obtained at $Z_R = 10 \text{ cm}$ using the open $A_{\text{jaw}}$ field).

Figure 18 Graphs of the OCR$_{\text{calc}}$ (including its components) and OCR$_{\text{meas}}$ (in points) datasets, with the $Y_{\text{beam}}$ value varied and $X_{\text{beam}} = 0 \text{ cm}$ on the isocenter plane at a reference depth of $Z = 10 \text{ cm}$, for $A_{\text{MLC}} = 5 \times 5 \text{ cm}^2$ and $A_{\text{jaw}} = 15 \times 15 \text{ cm}^2$ with the use of each of the four wedges in the direction of the $Y_{\text{beam}}$ axis. When using the 15°, 30° and 45° wedges, we set square jaw fields of $A_{\text{jaw}} = 5 \times 5 - 20 \times 20 \text{ cm}^2$ When using the 60° wedge, we set square jaw fields of $A_{\text{jaw}} = 5 \times 5 - 15 \times 15 \text{ cm}^2$. Figures 19a-c show the OCR$_{\text{calc}}$ (including its components) and OCR$_{\text{meas}}$ datasets for 10 cm, with the use of the 45° wedge for a combination of $A_{\text{MLC}} = 5 \times 5 \text{ cm}^2$ and $A_{\text{jaw}} = 15 \times 15 \text{ cm}^2$ fields: diagram (a) is for $X_{\text{beam}} = 0 \text{ cm}$; diagram (b) is for $X_{\text{beam}} = 1.25 \text{ cm}$; and diagram...
Finally, we calculated and measured the OCR($X_{\text{beam}}$, $Y_{\text{beam}}$) datasets, with the $X_{\text{beam}}$ value varied and $Y_{\text{beam}} = 0, -1.25$ and -3.75 cm on the isocenter plane at each reference depth of $Z_0 = 2.5, 5$ and 10 cm, using the four wedges in the direction of the $X_{\text{beam}}$ axis. When using the 15°, 30°, and 45° wedges, we set square jaw fields of $A_{\text{jaw}} = 5 \times 5 - 20 \times 20$ cm² for an MLC field of $A_{\text{MLC}} = 5 \times 5$ cm². When using the 60° wedge, we set square jaw fields of $A_{\text{jaw}} = 5 \times 5 - 15 \times 15$ cm² for an MLC field of $A_{\text{MLC}} = 5 \times 5$ cm². Figures 20a-c show the OCR$_{\text{calc}}$ (including its components) and OCR$_{\text{meas}}$ datasets for $Z_0 = 10$ cm with the use of the 45° wedge for a combination of $A_{\text{MLC}} = 5 \times 5$ cm² and $A_{\text{jaw}} = 15 \times 15$ cm² fields: diagram (a) is for $Y_{\text{beam}} = 0$ cm; diagram (b) is for $Y_{\text{beam}} = -1.25$ cm; and diagram (c) is for $Y_{\text{beam}} = -3.75$ cm. These OCR$_{\text{calc}}$ and OCR$_{\text{meas}}$ results clearly indicate variations in X-ray beam attenuation along the direction of wedge insertion. With respect to each of the diagrams, we obtained OCR$_{\text{cont}} = 0$, OCR$_{\text{MLC}}^{\text{calc}} = 0$, OCR$_{\text{MLC}}^{\text{meas}} = 0$ and OCR$_{\text{wedge}}^{\text{calc}} = 0$ and OCR$_{\text{wedge}}^{\text{meas}} = 0$ for all the calculation points (because the contaminant electrons and the secondary electrons from the MLC and wedge devices cannot reach each of the calculation points) and we obtained OCR$_{\text{cont}}^{\text{calc}} = 7.5 \times 10^{-5}$; OCR$_{\text{MLC}}^{\text{calc}} = 0$ and OCR$_{\text{wedge}}^{\text{calc}} = 0$, near the point of $X_{\text{beam}} = 0$ cm. Figure 20a shows waveform dose distributions in the left- and right-hand regions that are outside the MLC field but within the jaw field, where the pairs of A- and B-MLC leaves are just closed. In the waveform dose distributions, clearly showing X-ray leakages in the corresponding region. Almost the same calculation accuracy was also observed for the other OCR datasets.

waves repeated (reflecting the geometrical features of the half leaves of types 1 and 2 as shown in Figures 12 and 13, and clearly showing X-ray leakages in the corresponding region). Almost the same calculation accuracy was also observed for the other OCR datasets.

Figures 21a-d show the OCR$_{\text{calc}}$ (including its components) and OCR$_{\text{meas}}$ datasets for $Z_0 = 2.5$ cm with the use of the 60° wedge for a combination of $A_{\text{MLC}} = 5 \times 5$ cm² and $A_{\text{jaw}} = 15 \times 15$ cm² fields: diagram (a) is for $Y_{\text{beam}} = 0$ cm (details of the lower dose region are shown in diagram (b)); diagram (c) is for $Y_{\text{beam}} = -1.25$ cm; and diagram (d) is for $Y_{\text{beam}} = -3.75$ cm. Almost the same calculation accuracy was also observed
for the other OCR datasets. It should be noted that the dose leakage characteristics of the MLC are almost the same as those obtained by using a Monte Carlo simulation model [25] (Figures 20a, c and Figures 21a, d).

As the above-described PDD and OCR datasets show, the OCR datasets can, in general, reflect levels of dose calculation accuracy to a greater extent than the PDD datasets can. One of the most basic functions for a given linear accelerator is the OCR source function, defined in an open infinite A_{jaw} field (equation 23). As the OCR source function used in this study shows, it may not be reasonable to assume that the OCR source function is determined only by the off-axis distance on the isocenter plane; instead, it should generally be determined by the 2D position of (X₀, Y₀). Moreover, the magnitude of \( p_{\text{wedgefactor}} \) for each wedge should be determined after acquisition of an accurate OCR source dataset.

We performed theoretical and experimental studies on 10-MV X-ray dose calculations in water phantoms with multileaf collimation (MLC) and/or wedge filtration using a linear accelerator equipped with (in order from the source side) a pair of upper jaws, a pair of lower jaws, an MLC and a wedge filter. The dose calculation simulations were
performed, focusing on percentage depth dose (PDD) and off-center ratio (OCR) datasets.

The dose calculations were based on a convolution method using primary and scatter dose kernels formed for energy bins of X-ray spectra reconstructed as a function of the off-axis distance. We used the MLC leaf-field output subtraction method to calculate the in-air beam intensity for points on the isocenter plane for an open MLC field under a given jaw field, employing a small, extended radiation source on the X-ray target and a large, extended radiation source on the flattening filter. The in-air beam intensity was then decomposed into each energy-bin component ($E_i$) of the reconstructed X-ray spectra.

The 3D structures of the jaw collimator, MLC and wedge devices were replaced with 2D plates for simple dose calculation. Then-phantom dose calculation was performed by treating the phantom, the wedge, and the MLC as parts of a unified irradiated body, where we proposed to use a factor of $\mu_{\text{med}}(E_i)/\mu_{\text{water}}(E_i)$ (the relative attenuation factor) for each energy-bin component ($E_i$), instead of the relative electron density ($\rho_e$), for the medium of each volume element within the unified irradiated body, where $\mu_{\text{med}}(E_i)$ and $\mu_{\text{water}}(E_i)$ are the linear attenuation coefficients for $E_i$ photons of the volume element material and water.

Conclusions

It is confirmed that, as the MLC leaf-blocked section width became narrow, the in-phantom dose calculation effect due to nonuniform incident beam intensities became great. A correction factor was then introduced for each $\Delta V$ element in the phantom. The in-phantom dose was generally separated into nine dose components: (a) the primary and scatter dose components produced in the phantom, (b) the primary and scatter dose components emanating from the MLC, (c) the primary and scatter dose components emanating from the wedge body, (d) the primary and scatter dose components emanating from the wedge holder, and (e) the contamination dose component caused by the electrons emanating from the treatment head and the air volume.

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Conflicts of interest

This study was carried out in collaboration with Technology of Radiotherapy Corporation, Tokyo, Japan. This sponsor had no control over the interpretation, writing, or publication of this work.

Supplementary data

Supplementary data associated with this article can be found, at http://nobleresearch.org/doi/10.14312/2399-8172.2017-2. These data include appendix- A, B, C, and D.

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