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Technical notes

Parameterization of electron beam output factor

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ABSTRACT

Electron beam dose distribution is dependent on the beam energy and complicated trajectory of particles. Recent treatment planning systems using Monte Carlo calculation algorithm provide accurate dose calculation. However, double check of monitor units (MUs) based on an independent algorithm is still required. In this study, we have demonstrated single equation that reproduces the measured relative output factor (ROF) that can be used for MU calculation for electron radiotherapy. Electron beams generated by an iX (Varian Medical Systems) and a PRIMUS (Siemens) accelerator were investigated. For various energies of electron beams, the ROF at respective d_{max} were measured using diode detector in a water phantom at SSD of 100 cm. Curve fitting was performed with an exponential generalized equation $ROF = \alpha(\beta - e^{-\gamma R})$ including three variables (α, β, γ) as a function of field radius and electron energy. The correlation coefficients between the ROF measured and that calculated by the equation were greater than 0.998. For ROF of Varian electron beams, the average values of all fitting formulas were applied for two of the constants; α and β. The parameter γ showed good agreement with the quadratic approximation as a function of mean energy at surface (E_0). The differences between measured and calculated ROF values were within ±3% for beams with cutout radius of ≥1.5 cm for electron beams with energies from 6 MeV to 15 MeV. The proposed formula will be helpful for double-check of MUs, as it requires minimal efforts for MU calculation.

Introduction

Electron beams are used in cancer treatment, especially for superficial tumors as well as boost to a larger photon-beam treatment such as head and neck and breast cancer. The dose distribution from electron beams is difficult to predict due to complex dependence on the beam energy and complicated trajectory of particles affected by scattering foils, collimating elements, such as applicator or electron inserts, and patient body. The dose per monitor unit (MU) can be calculated by the relative output factor (ROF), which is defined as the ratio of the dose in water at reference point with a custom cutout to the dose under the reference field in calibration condition [1,2]. The dose is prescribed to d_{max} at the center of the field, and the ROF for the patient insert is measured in water in order to calculate the MU to deliver. As a result, the ROF of a specific treatment is usually measured individually in order to achieve an acceptable accuracy. These patient-specific electron measurements are time consuming and prone for significant error due to selection of detector and respective d_{max}.

There are many publications on analytical methods to calculate the percent depth dose (PDD) [3] and/or ROF for electron beams, including the sector-integration method [4,5], Gaussian pencil model plus collimator scattering [6,7], two-source model [8], and a method based on the lateral build-up ratio [9–11]. The current generation of treatment planning systems for clinical use depend on pencil-beam algorithms [12,13]. The algorithm approximates the spatial distribution of pencil beams with Gaussian functions [14,15]. Monte Carlo simulation does not attempt to generalize the overall behavior of the electron beam but simulates the full physical interactions of the various beam constituents. Monte Carlo based calculation algorithms have shown superior dose distribution and dose calculation especially with inhomogeneities and/or highly irregular field geometries [16–18]. However, full simulations often take much longer time to calculate.

Even though TPS could provide ROF for a small field, it needs to be double checked in most cases in a shorter time. A number of

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studies have demonstrated methods to calculate ROF, but still many clinics prefer to measure ROF for each treatment field. The special techniques which require programming skills to develop a software or purchase of a new TPS cannot be implemented in most clinics. In this study, we have parameterized ROF of electron beams and demonstrated a single equation that reproduces the measured ROF values. With this method, the ROF can be calculated with a simple calculator.

Methods and materials

Measurement of the output factors

Electron beams from a Varian iX accelerator (Varian Medical Systems, Palo Alto, CA) were investigated in this study. Circular inserts of various radii were made for 6 × 6 cm^2, 10 × 10 cm^2, 15 × 15 cm^2, 20 × 20 cm^2 and 25 × 25 cm^2 electron applicators. The radii of circular inserts investigated for electron beams from Varian linac were listed in Table 1. The inserts were manufactured from the low temperature melting alloy, Cerrobend. The ROFs at d_{max} were measured using IBA EFD 3G Electron Dosimetry Diode Detector 322-605 (IBA Dosimetry GmbH, Schwarzenbruck, Germany). Measurements were performed in a water phantom at SSD of 100 cm. Output factors for high-energy electron beams in radiotherapy are normally measured according to international dosimetry protocols [1,2]. ROF values of various circular inserts for PRIMUS (Siemens, Concord, CA) were collected for 10 × 10 cm^2 applicator. Nominal energy and mean energy at surface (E_0) for two accelerators are listed in Table 2.

Curve-fitting method

The ROF was calculated using CurveExpert ver. 2.0.4 software. Curve fitting was performed with an exponential function as below:

$$ROF = \alpha\left(\beta - e^{-\gamma R}\right) \quad (1)$$

where α, β, and γ are constants, and variable *R* represents the electron field insert radius. To evaluate the agreement between measured and calculated ROF values, a Pearson correlation coefficient was calculated using the following formula:

$$correlation\ coefficient = \frac{\sum_i \left(Fm_i - \overline{Fm}\right)\left(Fc_i - \overline{Fc}\right)}{\sqrt{\sum_i \left(Fm_i - \overline{Fm}\right)^2}\sqrt{\sum_i \left(Fc_i - \overline{Fc}\right)^2}} \quad (2)$$

where F_m and F_c represent measured and calculated values of ROF.

Results

Figure 1 shows the measured ROF plotted with the radius of the inserts. The fitted curves are illustrated as lines. The correlation coefficient between the calculated and the measured ROF for all energies and cone sizes were greater than 0.998, indicating extremely good fit of the calculated curves. The range of the differences between the calculated and measured ROF were between −1.89% and +2.65%. The cone sizes did not show significant effects on the radius dependence of ROF at the same SSD; variation coefficients among various cone sizes were less than 2.3% for all energies and radii ≥0.5 cm.

Figure 2 shows the constants α, β, and γ calculated for each energy and cone size. There was no correlation between α, β and energy. The parameter β showed smaller deviation among various cone sizes than α. These two parameters were considered as constants. In contrast, the parameter γ showed quadratic energy-dependence (Eq. (3)):

$$\gamma = \gamma_1 E_0^2 + \gamma_2 E_0 + \gamma_3 \quad (3)$$

where E_0 represents the mean electron energy at the surface of the phantom. The quadratic approximation illustrated as a curve showed good agreement with the γ values ($r^2 \geq 0.97$), although 18- and 21-MeV of Siemens data did not show good fittings. These two energies were excluded from this study because small fields and high energies are not clinically used. For Varian data, the cone sizes did not show significant effects on α, β and γ; variation coefficients among various cone sizes were less than 4% for all energies and three parameters. Therefore, the parameterization of ROF was considered as a function of energy and radius. The coefficients of "generalized" equation of the ROF are listed in Table 3.

Figure 3 shows the measured ROF values and the generalized equations of Varian accelerator. The correlation coefficients between the calculated and the measured ROF for all energies and cone sizes were greater than 0.998. The differences between the calculated and measured ROF are illustrated in Fig. 4. The differences for various radii and cone sizes were well within ±3% for the radius ≥1.5 cm.

The curve fitting was also conducted for ROF of electron beams generated by Siemens PRIMUS accelerator. The generalized function was calculated for ≤15 MeV beams as high energy did not show good fitting. Figure 5a shows measured ROF values and generalized fitting curves of Siemens accelerator. Figure 5b shows the differences between measured and calculated ROF values plotted with cutout size. The differences for radius ≥1.5 cm cutout size were within ±3% for energies ≤15 MeV, although the differences of 18- and 21-MeV for 2 cm cutout were 3.5% and 3.7%, respectively (data not shown).

Discussion

As mentioned previously, several methods for calculation of ROF [4,6–11] have been reported. These algorithm attempt to predict the ROF of an irregular electron field using analytical methods based on measurements. However, most of them investigated for only one type of accelerator. In this study, we developed a method to predict the ROF of electron beams with a simple equation. This

Table 1
The radii of circular inserts investigated for electron beams from Varian linac.

Cone sizes	Radii of circular inserts [cm]								
	0.5	1	1.5	2	3	4	5	7.5	10
6 × 6 cm^2	x	x	x	x	x				
10 × 10 cm^2	x	x	x	x	x	x	x		
15 × 15 cm^2	x	x	x	x	x	x	x		
20 × 20 cm^2	x	x	x	x	x	x	x	x	
25 × 25 cm^2	x	x	x	x	x	x	x	x	x

Table 2
Nominal energy and mean energy at surface (E_0) of two accelerators.

Varian iX		Siemens PRIMUS	
Nominal [MeV]	E_0 [MeV]	Nominal [MeV]	E_0 [MeV]
6	5.48	6	5.13
9	8.39	9	8.2
12	11.50	12	11.15
16	15.40	15	14.49
20	19.00	18	17.66
		21	20.07