Design and Implementation of a Monte Carlo Framework for Assessment of Spoiler Applications in Abutting Electron Fields

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ABSTRACT

Background: Field matching problems in abutting electron fields can be managed by using spoilers.

Objective: The aim of this study was to design a Monte Carlo framework for the assessment of spoiler application in abutting electron fields.

Methods: A Siemens Primus treatment head was simulated for a 5 MeV electron beam using BEAMnrc and DOSXYZnrc, EGSnrc user codes. Validation of beam model was done by measurement using a MP3-M water tank and a Semi-flex Chamber-31010 (PTW, Freiburg, Germany). An in-house routine was developed to calculate the combined isodose curves resulting from simulated adjacent fields. The developed framework was analyzed using PMMA and chromium spoilers.

Results: The penumbra width increased from 27.5 mm for open fields to 42 mm for PMMA and 40 mm for chromium. The maximum junction dose reduced from 115% for open fields to 107% for PMMA and 108% for chromium. R90 reduced about 6 mm for PMMA and 3 mm for chromium. Uniformity index reduced from 93% to 77% for both spoilers. Surface dose increased from 79% to 89% for PMMA and 88% for chromium.

Conclusion: Using spoilers, penumbra width at the surface increased, size and depth of hot spots as well as the therapeutic range decreased and dose homogeneity at the junction of abutting electron fields improved. For both spoilers, the uniformity index reduced, and surface percent dose increased. The results of this research can be used to optimize dose distribution in electron beam treatment using abutting fields.

Keywords
Spoilers, Abutting Fields, Electron Beam, Radiotherapy

Introduction

The main criterion in radiation therapy is to irradiate tumor volume with maximum dose while protecting vital organs and surrounding normal tissue from unnecessary irradiation. Using electron beams for treatment of superficial tumors is one way to achieve the above criterion. The most important characteristic of clinical electron beams is the sharp dropoff in dose beyond the therapeutic range (R_{90}). In cases where the collimator field is not large enough to cover the entire target volume or tumor dose distribution is not acceptable due to patient anatomy, abutting electron fields are used. Electron beam divergence

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and lateral scattering may lead to significant dose inhomogeneity and creation of hot or cold points in the junction region [1]. Different solutions have been proposed to solve the problem of hot and cold spots in abutting electron fields. The simplest technique is the use of an optimal skin gap between the two adjacent electron fields. However, determination of an optimal skin gap is complicated due to the increased lateral scatter of low energy electrons. Additionally, small deviations in field separation may lead to significant variation in dose in the overlap region [1-3].

A. M. Kalend et al have suggested the use of a beam-edge modifier to broaden electron beam penumbra. This device is a high-density triangular-toothed comb and its function is to reduce electron intensity by selective absorption of electrons. However, dose ripple effect and aligning of the device are limitations of this method [4].

Alternatively, use of electron spoiler was proposed in different studies for a wide range of applications [2, 5, 6]. In Mckenzie's study [2], a tissue equivalent resin was used at the end of electron applicator in order to produce the penumbra broadening required for desirable beam matching. The penumbra width is defined as the lateral distance between 80% and 20% isodose lines. The following advantages for using a spoiler were mentioned: overlap or gap is not required between adjacent fields, and spoiler design is independent of the applicator cone characteristics. The following relationships between penumbra widths, beam energy and spoiler material specifications were proposed:

$$P_m^2 = P_0^2 + P_s^2 \qquad (1)$$

$$P_s\,(\mathrm{mm}) = kLz^{1/2}E^{-1} \qquad (2)$$

P_m and P_0 are penumbra widths at the phantom surface with and without spoiler in place, respectively. P_s is the broadening resulting from the contribution of the spoiler, E (MeV) is the beam energy, L (mm) is the distance from the inner face of the spoiler to the phantom surface, z (mm) is the thickness of the spoiler and k is a constant. Value of k depends on spoiler's density and scattering power. Therefore, it was recommended to determine the value of k by measurement for other spoiler materials [2]. Further measurements are required in order to predict the effect of beam spoilers on dose distribution in depth, both inside and outside the field junction. Dose distribution characteristics include R_{90}, surface dose percentage, hot spot specifications and dose uniformity index. A hot spot is an area of at least 2 cm^2, out of the target which receives a higher dose than the target dose [1]. Parameters that affect spoiled beam dose distribution include field size, depth, z, ρ, E and L [2]. Considering the number of influence factors, Monte Carlo simulation method can be used to evaluate the effect of adding a spoiler to produce uniform dose distribution in abutting fields.

The goal of this research was to design a Monte Carlo framework for the assessment of spoiler application in abutted electron fields. Using this framework, thickness of different spoilers for specific dose distribution criteria in the junction of abutting fields can be determined. This framework was implemented for a low energy electron beam, a low density and an intermediate density spoiler material.

Material and Methods

Siemens Primus linear accelerator was simulated for a 5 MeV nominal energy electron beam. After validating the simulation results, the impact of spoilers on dose distribution inside and outside the junction of abutting electron fields were investigated.

Simulation of Beam Model

In this work, a Monte Carlo model of Siemens Primus linear accelerator was simulated for a 5 MeV nominal energy electron beam using manufacture provided specifications. BEAMnrc and EGSnrc user code were used to simulate the treatment head in electron mode

[7-10]. The following component modules were used to simulate different head components: exit window (SLAB), primary and secondary scattering foils (CONESTAK), ion chamber (CHAMBER), collimating Y jaws (JAWS), X-multi leaf collimator (MLC), accessory slot 1 (CONESTAK), accessory slot 2 (CONESTAK) and applicator (APPLICAT) [11]. A circular electron beam (ISOURC=0) with radius equal to 0.1 cm was used. Particle related data were as follows: 5×10^7 particles, global cut-off energies for electron was 0.7 MeV and for photon was 0.01 MeV. The field size was 10×10 cm^2.

Dose Calculations

The resulting phase space file was used as a source for dose calculations for 10×10 cm^2 field size at SSD=100 cm in a $30\times30\times45$ cm^3 water phantom using DOSXYZnrc user code [12]. Voxel sizes (x×y×z) at different percent depth dose (PDD) and beam profile regions were set as follows: 1 cm×1 cm×0.2 cm in PDD build-up region, 1 cm×1 cm×0.5 cm beyond the build-up region and 1 cm×1 cm×0.5 cm for beam profile.

Verification of Electron Beam Model

An automatic MP3-M water phantom tank, MEPHYSTO mc^2 software platform and a Semi-flex Chamber-31010 with sensitive volume of 0.125 cm^3 (PTW, Freiburg, Germany) were used for dose distribution measurements. Moreover, the electron field size was 10×10 cm^2 and SSD=100 cm. Validation of developed beam model was done by comparing the measured and calculated depth and lateral dose distributions. The percentage difference of calculated and measured values was determined using the following formula ($\frac{|calculated\ dose - measured\ dose|}{measured\ dose}\times100$) and were used to compare with acceptance criterion [13]. The acceptance criterion for simulated beam model is 2% difference for PDD build up region and 3% difference beyond the build-up region and for beam profile is 2% difference at the edges and 1% difference in other regions [14].

Simulation of Spoiler

Simulation of spoilers (using SLAB component module) placed at the end of the electron applicator, was done using previously validated phase space file for a 5 MeV nominal energy and 10×10 cm^2 field size. PMMA and chromium were selected as low and intermediate density materials, respectively. A thickness of 5 mm was selected for PMMA as the reference thickness. For chromium, the thickness to produce the same angular spread as 5mm PMMA was calculated to be 0.3 mm, using the radiation length (X0) concept. Radiation length is the mass thickness in which the transmitted electron beam energy reduces to 1/e of its original energy, due to radiative interactions. The impact of these materials as spoilers on dose distribution inside and outside of the junction between abutting electron fields was investigated.

Calculation of Dose Distribution in Abutting Electron Fields

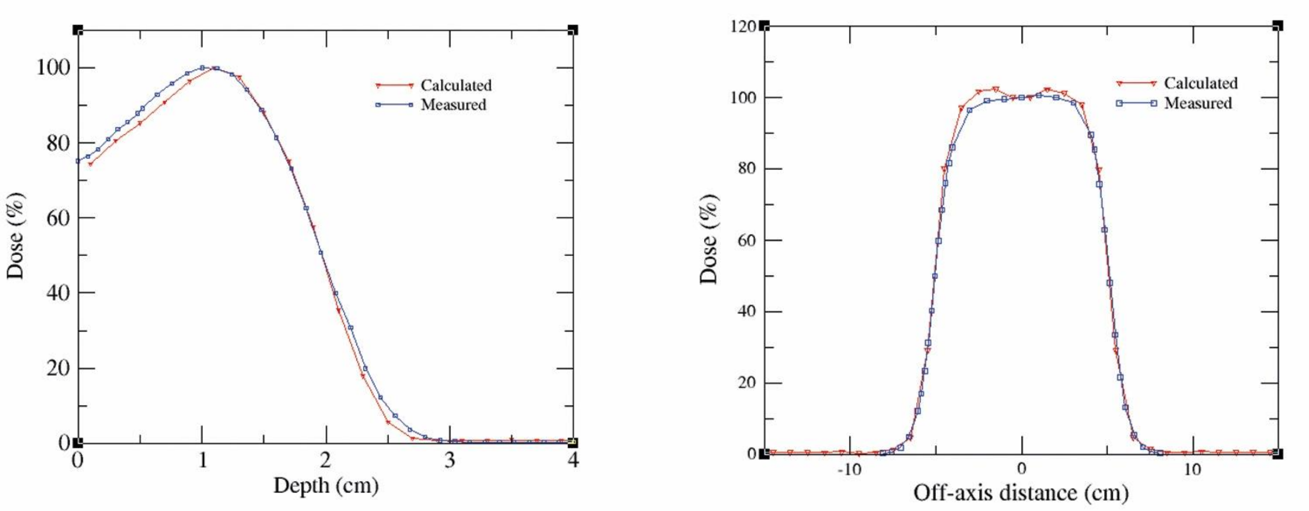
An in-house routine was developed in order to calculate the combined isodose curves resulting from the two simulated abutting fields. SSD was 100 cm and the gantry angle for both fields was 0°. Resultant isodose curves were calculated and the following parameters were estimated: R_{90}, surface dose percentage is relative to dose at depth of maximum dose (d_{max}), hot spots specifications and dose uniformity index.

P_0, P_m and P_s were calculated at the surface using isodose curves and equation (1). The value for k was calculated using equation (2). In addition, uniformity index produced by different spoilers was compared. Uniformity index is defined as the ratio of width of 90% and 50% isodose lines at the depth of half of 85% depth dose [1]. Moreover, depth of 90% dose (R_{90}), inside and outside the junction region, were compared to the open beam for different spoilers.

Results

Verification of the developed 5.9 MeV electron beam model was done by comparing the calculated and measured dose distributions. The maximum percentage difference between calculated and measured PDD was 1%, except for the build-up region in which the difference was 2%. The difference between calculated and measured profile was 2% at the edges of the field and less than 1% in other regions (Figure 1).

Figure 2 illustrates the combined isodose distribution in water phantom irradiated with two abutting fields without spoiler (open fields). The combined isodose patterns of abutting electron fields transmitted through PMMA and chromium spoilers are shown in Figures 3



(a) (b)

Figure 1: Comparison of calculated 5.9 MeV and measured 5 MeV dose distributions for 10×10 cm^2 field size at 100 cm SSD, (a) percent depth dose curves (b) dose profile curves

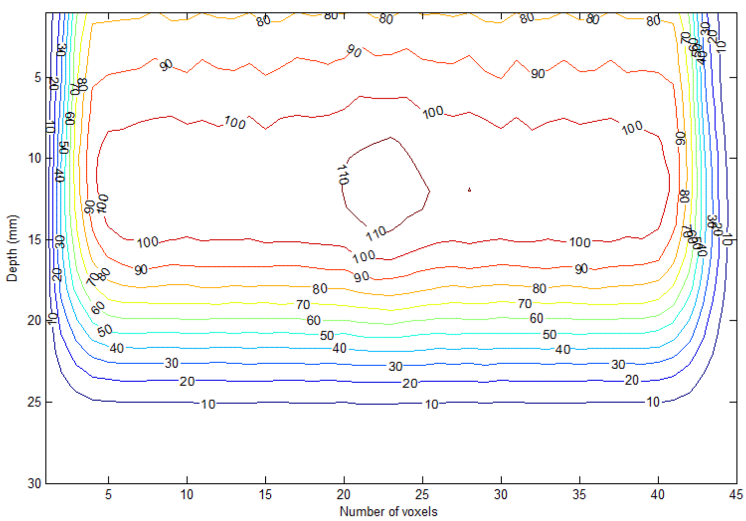


Figure 2: Combined isodose distribution calculated for two abutting 5 MeV, 10×10 cm^2 open (without spoiler) electron fields, normalized to dose at the depth of maximum dose outside the junction.

and 4, respectively. Depth dose distributions at the field junction for both spoilers are shown in Figure 5.

The values for P_m, P_s, k (using equation (2)), uniformity index, R_{90} inside and outside the junction and surface dose percentage were calculated for PMMA and chromium and results are shown in Table 1.

Discussion

In this work, a Monte Carlo simulation framework was designed in order to evaluate the effect of spoilers on dose distribution in depth, both inside and outside abutted electron field junctions. This framework was implemented for PMMA and chromium spoilers and the results were analyzed using an in-house

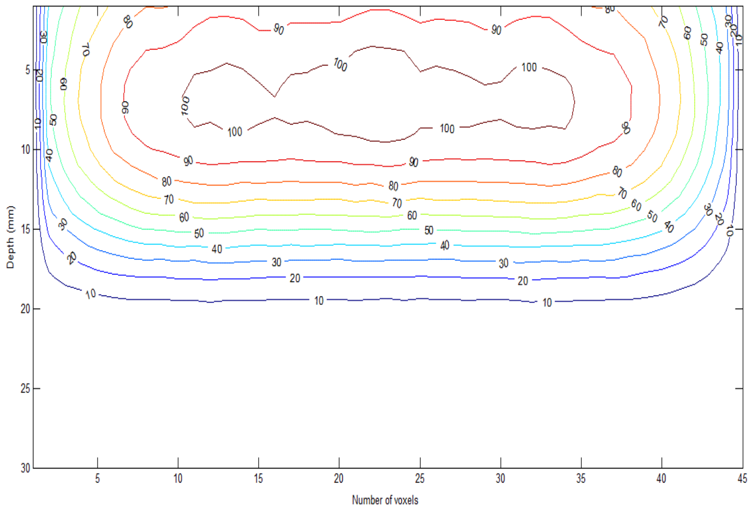


Figure 3: Combined isodose distribution calculated for two abutting 5 MeV, 10×10 cm^2 electron fields with 5 mm PMMA spoiler, normalized to dose at the depth of maximum dose outside the junction.

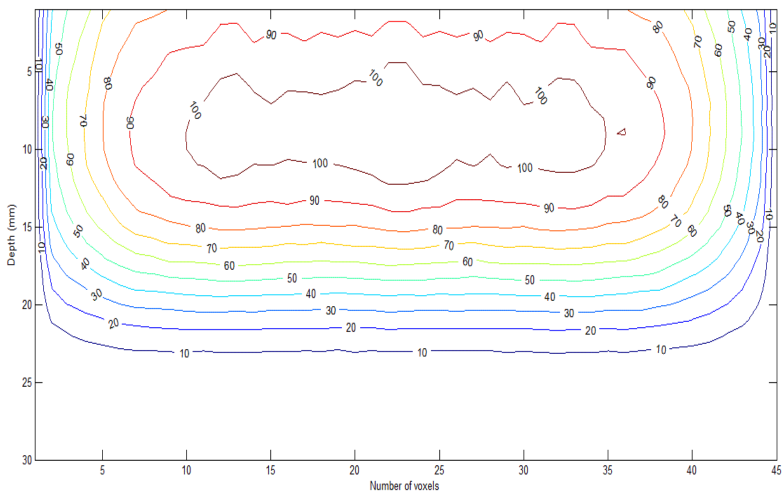


Figure 4: Combined isodose distribution calculated for two abutting 5 MeV, 10×10 cm^2 electron fields with 0.3 mm chromium spoiler, normalized to dose at the depth of maximum dose outside the junction.

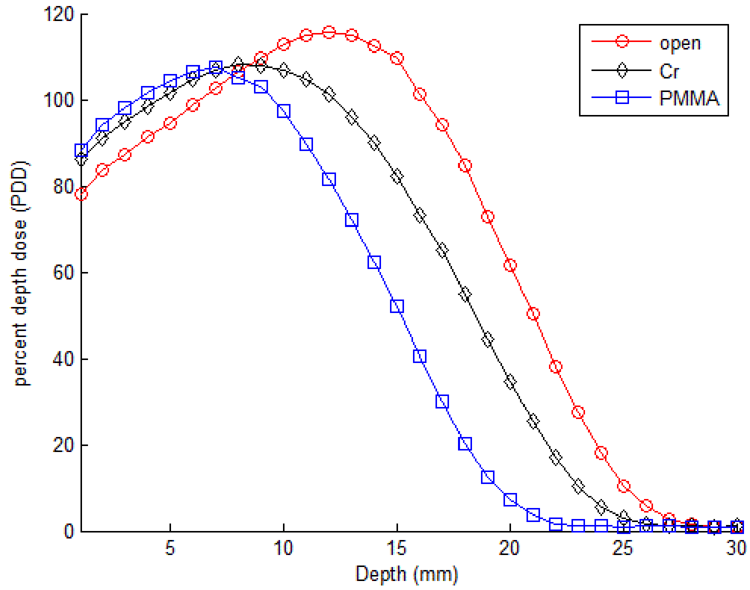


Figure 5: Percent depth dose curves at the junction of abutting 5 MeV, 10×10 cm^2 electron fields with and without chromium and PMMA spoilers, normalized to the dose at the depth of maximum dose outside the junction.

Table 1: Dose distribution parameters produced using PMMA and chromium spoilers for two abutting 5 MeV, 10×10 cm^2 electron fields.

spoiler	P_m (mm)	P_s (mm)	P_0 (mm)	k	Uniformity index	R_{90} inside the junction (mm)	R_{90} outside the junction (mm)	Surface dose (%)
open (without spoiler)	_	_	27.5	_	0.93	16.5	15.5	79
PMMA	42	31.74	-	1.26	0.77	10	9.5	89
chromium	40	29.04	-	5.08	0.77	13	12.5	88

routine. Using spoilers, penumbra width at the surface increased, size and depth of hot spots, as well as the therapeutic range was decreased and dose homogeneity improved at the junction of abutting electron fields. The amount of junction dose without spoiler at 12 mm depth was 115% with respect to dose at d_{max}. Using PMMA spoiler, both percent dose and depth of hot point reduced to 107% and 7.1 mm, respectively. For chromium 108% hot point was seen at the depth of 8 mm (Figure 5). Therefore, a reduction of about 7% in dose improved dose uniformity in this region due to broadening penumbra width. The value of P_s and therefore P_m produced by chromium spoiler was less compared to PMMA. The value of k for PMMA was in agreement with what reported by McKenzie [2].

R_{90} reduced both inside and outside the field junction for both spoilers. Reduction in R_{90} was more for PMMA, about 6 mm versus 3 mm for chromium in both regions. Thus, chromium is more suitable to be used as spoiler for the treatment of deeper tumors. According to

McKenzie [2], when using a spoiler, change in depth of a specific isodose line is expected to be equal to tissue equivalent thickness of the spoiler. Our results confirmed this suggestion for PMMA approximately, but not for chromium. This is because the thickness of 0.3 mm for chromium was selected to produce the same angular spread but not the same energy loss [15].

Moreover, uniformity index was reduced due to penumbra broadening for both spoilers. This is due to movement of high value isodoses toward the field interior while the low value isodoses remain without change [2]. Thus, P_m increased and led to a decrease in uniformity index. Therefore, when using a spoiler, field size should be larger. Uniformity index is used to calculate the width of uniform section of a field. For example, for the spoilers evaluated in this research, each 10×10 cm^2 field covered a 7.7 cm uniform width (0.77×10 cm^2) compared to 9.3 cm width (0.93×10 cm^2) for the open field.

Finally, surface percent dose increased because of increase in electron angular spread. When using a spoiler, electron angle of scatter at the surface increases. Therefore, fluence at the surface increases by 1/cosθ, where θ is the angle of scatter, while fluence at the depth of maximum remains unchanged [1], hence increasing the percent surface dose with respect to dose at d_{max}. The framework developed and implemented in this research can be used to optimize dose distribution in electron beam treatment using abutting fields.

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Conflict of Interest

None

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