Original Article

Estimation of Backscatter from Internal Shielding in Electron Beam Radiotherapy Using Monte Carlo Simulations (EGSnrc) and Gafchromic Film Measurements

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Abstract

Purpose: The purpose of the study was to estimate the backscatter electron dose in internal shielding during electron beam therapy using Monte Carlo (MC) simulations and Gafchromic film measurements. **Materials and Methods:** About 6 and 9 MeV electron beams from a Varian 2100C linac were simulated using BEAMnrc MC code. Various clinical situations of internal shielding were simulated by modeling water phantoms with 2 mm lead sheets placed at different depths. Electron backscatter factors (EBF), a ratio of dose at tissue-shielding interface to the dose at the same point without the shielding, were estimated. The role of 2 mm aluminum in reduction of backscatter was investigated. The measurements were also performed using Gafchromic films and results were compared with MC simulations. **Results:** For particular beam energy, the EBF value initially increased with depth in the buildup region and then decreased rapidly. The highest value of EBF for both the energies is nearly same though at different depths. Decreased EBF was observed for 9 MeV beam in comparison to the 6 MeV beam for the same depth of shielding placement. Two millimeter aluminum reduced the backscatter by nearly 25% at maximum backscatter condition for both the energies, though the effectiveness slightly decreased at higher energy. The range of backscatter electrons was varying from 5 to 12 mm in the upstream direction from the interface. The Gafchromic film-measured EBF and MC-simulated EBF were matching well within the clinically acceptable limits except in close vicinity of tissue-lead interface. **Conclusions:** This study provides an important clinical data to design internal shielding at the local clinical setup and confirms applicability of MC simulations in backscatter dose calculations at interfaces where physical measurements are difficult to perform.

Keywords: Electron backscatter, electron radiotherapy, internal shielding, Monte Carlo simulation

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Introduction

Electron beam therapy (EBT) is widely practiced to treat superficial lesions such as those of the eyelid, ear, lip, buccal mucosa, and nose. The advantage of EBT is the sharper dose fall off as compared to photon beams resulting in reduced dose to the region beyond the targeted depth. However, in some clinical situations where the critical organ lies in close proximity to the treatment tissue, a thin layer of high atomic number material such as lead or tungsten is inserted between treatment tissue and the underlying critical tissue for effective sparing of the latter. Such an arrangement is called as internal shielding [Figure 1]. In addition to the very high attenuation of the electrons in the forward direction, there is also backscattering of electron from the shielding material. These backscattered electrons deposit their energy into the upstream tissue and enhance the dose to the tissue at the tissue-shielding interface. The dose enhancement depends on parameters such as incident electron beam energy, thickness of tissue volume above the shielding sheet, angle of electron beam incidence on surface, and presence of a layer of low atomic number material on top of the sheet.[1-3] It is important to estimate the amount of dose enhancement due to the backscatter electrons from the shielding material to enable

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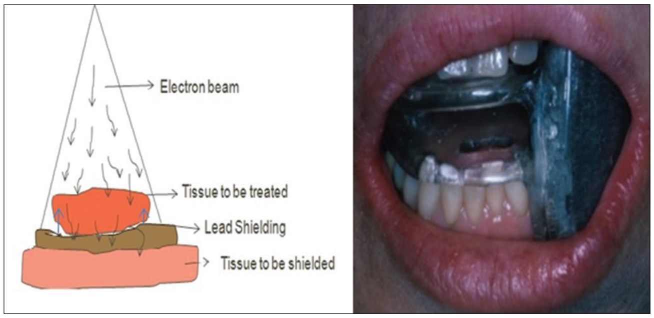

Figure 1: Schematic diagram of a typical internal shielding arrangement and actual photograph of buccal mucosa treatment using internal shielding

measures for mitigation of potential toxicities. The backscatter can be reduced by covering the lead/tungsten shield with a layer of aluminum (a low atomic number material) or a layer of tissue-equivalent material (bolus).[3]

The relative dose enhancement can be represented in terms of electron backscatter factor (EBF). The EBF is defined as the ratio of the dose at tissue-lead interface to the dose at the same point in the absence of lead shielding.[4] By definition, EBF is a point quantity; it is difficult to measure it using finite-size volumetric devices like an ion chamber.[1] The size of the measuring device should be small enough to be approximated as a point measuring device and also its presence should offer minimum perturbation to the prevailing electron fluence. Several studies have been done to estimate EBF using various detectors (parallel plate ionization chamber, thermoluminescent dosimeter, and films) and theoretical calculations using Monte Carlo (MC) simulations.[1] Different MC codes such as EGS4, MC N-particle, and GEometry ANd Tracking have been successfully used for the purpose. The EBF estimates with these MC simulations have been found to be accurate and reliable when compared with physical measurements.[1,5,6] The advantages of the MC simulations in EBF estimation as compared measurements are (1) small voxel size (<1 mm) near the interface and (2) no perturbation due to physical size of the detector. Once a particular MC model is validated by physical measurements, the EBFs can be calculated for different clinical settings saving time and human efforts.

Literature shows a large spread in EBF values, especially in the energy range below 4 MeV at lead-tissue interface.[1,4-12] The superficial lesions are largely treated with 6 or 9 MeV electron energy and the mean energy at the lead interface can be given by the International Commission on Radiation Unit report 35[13] as

$$Em = E_0 \ (1 - z / Rp) \qquad (1)$$

where Rp is the practical range of electrons and E_0 is the mean energy at the surface.

Thus, for most of the clinical situations, the mean energy at the lead interfaces about 4 MeV or less. The large spread ranging between 5% and 20% in the EBF values has been attributed to the measurement uncertainties by some authors.[7-12] However, some others have also attributed this spread to the varied electron spectra produced by different linacs. De Vries and Marsh have simulated Siemens Artiste electron beam and calculated EBF values.[14] They also derived an empirical equation to calculate EBF from lead shielding for their local linac.

The commercially available treatment planning systems (TPS) till recently were unable to estimate the EBF values with desired accuracy due to the limitations of the available calculation algorithms. Of late, some planning systems have incorporated optimized MC codes for electron beam calculation. Eclipse (version 13.5) from M/s Varian Medical Systems Palo Alto, CA, USA, uses an implementation of the macro-MC algorithm, called electron MC, which utilizes precalculated probability distribution function. This method reduces the solving of complex scattering interactions to a simple sphere-stacking problem using table lookups and results in a considerable improvement in calculation speed.

In this study, the local treatment machine Varian 2100C (M/s Varian Medical Systems Palo Alto, CA, USA) was simulated using BEAMnrc MC method for two widely used electron energies 6 and 9 MeV. The EBFs were calculated for different positions of the lead sheet in a water phantom. The upstream percentage depth dose (PDD) was calculated using DOSXYZnrc to determine the range of the backscatter contribution at the lead/tissue interface. The TPS calculated PDDs were compared with MC calculated and film measured PDDs. The study provided systematic and clinically useful data on EBFs in a local setup when using lead shielding in EBT to treat superficial lesions, examined the efficiency of low atomic number material (aluminum) in reducing electron backscatter contribution.

Materials and Methods

Monte Carlo simulation of linac

MC code EGSnrc (4-r 2-3-1)[15] developed by the National Research Council of Canada was used to model the electron beam from the head of a Varian linear accelerator model 2100C (Varian Medical System, Palo Alto, CA, USA). The treatment head specifications were obtained from the manufacturer under nondisclosure agreement. BEAMnrc (version 2.0)[16] graphical user interface was used to generate phase-space files for 6 and 9 MeV electron beams at 100 cm source to surface distance (SSD) for a 10 cm × 10 cm field size. These phase space files were used to calculate central axis PDDs using DOSXYZnrc (version 1.1)[17] code in a 40 cm × 40 cm × 40 cm water phantom. We first started our simulations with the initial energy of primary electrons calculated using $E_0 = C \times R_{50}$, where C = 2.4 MeV/cm and R_{50} (cm) as taken from measurement data. This initial energy was further adjusted till the simulated PDD and measured PDD agree within ±2%. The final values of primary electron energy for 6 and 9 MeV electron beams were 6.75 and 10.44 MeV respectively.

The transport parameters were Electron CUT off energy = 700 KeV, Photon CUT off energy = 10 KeV, and Electron sub STEP length = 0.25. The Parameter Reduced Electron Step Transport

Algorithm II was used as the electron step algorithm with the user-adjustable parameters set at their default values.[18,19] Initial 500 million histories were simulated in BEAMnrc code and scored at a plane just above the surface of water phantom. The calculations took 10–15 h. The water phantom of 40 cm × 40 cm × 40 cm with voxel size 1 mm in z (depth) direction was simulated with DOSXYZnrc using phase-space files of the previous step. Two hundred million histories were simulated and PDD curves were extracted using STATDOSE program available with BEAMnrc package.

Validation of Monte Carlo simulations

Validation of MC model was performed by comparing simulated central axis PDD and the physically measured PDD curves in water phantom. Physical measurements were carried out in a three-dimensional scanning water phantom (radiation field analyzer [RFA] 300) using electron diodes (IBA EFD 3G Electron Dosimetry Diode Detector, from IBA Dosimetry System, Germany) and OmniPro Accept 7 (IBA Dosimetry system, Germany) acquisition software. International Atomic Energy Agency TRS398 protocol for high-energy electron dosimetry was followed in the measurements.

Monte Carlo simulation of electron backscatter

A layer of lead of thickness 2 mm was simulated at various depths in the 40 cm × 40 cm × 40 cm water phantom using DOSXYZnrc. The 2 mm thickness was found to be enough to provide saturation levels of backscatter as well as adequate shielding from 6 to 9 MeV electron beam to underlying tissues.[3] The lead sheet was simulated at depths of 0.5, 1.0, 1.5, 2.0, 2.5 cm for 6 MeV electron beam and 0.5, 1.0, 1.5, 2.0, 2.5 cm for 9 MeV electron beam. Figure 2 shows the MC simulated phantom geometry with lead sheet. To study the effect of low atomic number material (aluminum) in reduction of backscatter electrons, all the simulations were repeated with a layer of 2 mm aluminum above the lead sheet.

The number of histories in each simulation was set to 200 million and the voxel size was taken as 1 × mm 1 × mm 0.5 mm for x, y, and z, directions respectively. The central-axis PDDs were obtained using STATDOSE program and plotted in the MS Excel sheets. EBFs and electron backscatter intensity (EBI) were calculated as the ratio of dose with and without lead interface. The relative dose errors (uncertainties in dose in a voxel) were <1% in each simulation.

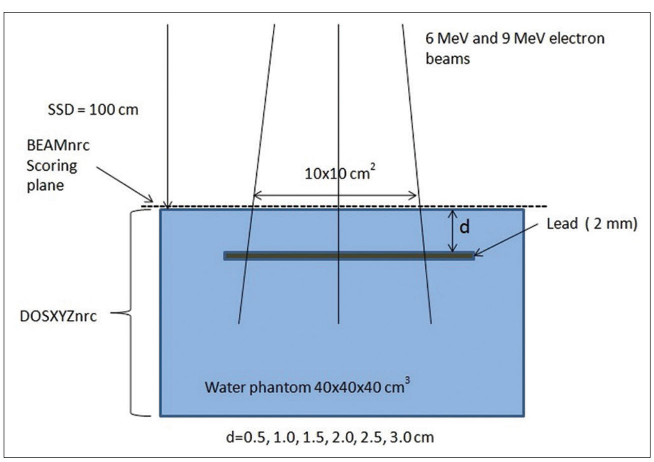

Figure 2: Schematic diagram of Monte Carlo simulation geometries of 6 and 9 MeV electron beams. Two millimeter lead sheet is placed at various depths d = 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 cm

Gafchromic EBT3 film measurement of electron backscatter

Measurements of electron backscatter were made using Gafchromic EBT3 films (ISP, Wayne, USA) to further validate the MC simulations. The Gafchromic film was chosen for measurements because of its properties such as dose linearity (1c–40 Gy), near tissue equivalence, little energy dependence, and dose rate independence in the electron beams. It is an ideal dosimeter for measurements in high gradient dose regions such as interface of heterogeneities where detector placement perturbs the electron fluence. The films being waterproof, were submerged into water phantom for measurements. The measurement geometry was kept similar to the simulation geometry [Figure 2]. The PDD measurements were done without lead using 2 cm wide strip of a film for both the energies, i.e., 6 and 9 MeV. The PDD measurements were also done with lead layer placed at 1.5 and 2.0 cm for both the electron energies. The film strips were precisely cut to make an insert of 2 mm lead sheet placed horizontally with respect to the film plane [Figure 3]. The lead sheet with the film was fixed in the water phantom with the help of thin acrylic bars keeping lead sheet perfectly horizontal and the film in the central axis plane. The depth of lead shielding was altered by changing the water level inside the phantom while maintaining the SSD 100 cm. To measure the PDD without the lead sheet the film strip was pasted with the acrylic bar and submerged in the water phantom. The films were scanned after 48 h to allow drying of the moisture on the film. The readings were then converted into dose using calibration curve.

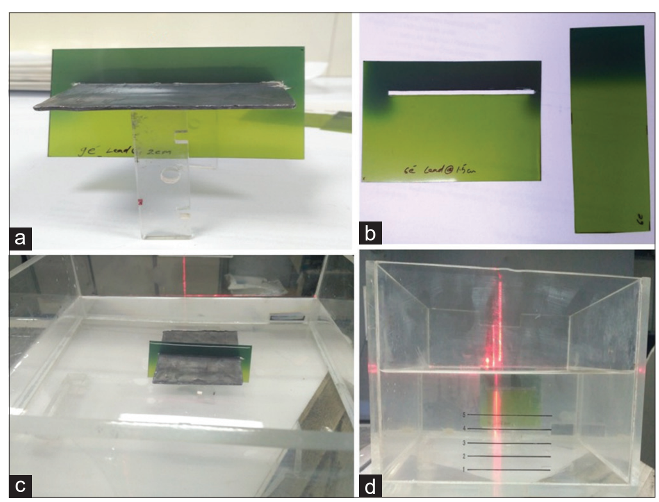

Figure 3: Photographs of Gafchromic film irradiations (a) film positioned in water phantom with 2 mm lead insert (b) irradiated film and percentage depth dose strip of 6 MeV (c) film placed in water phantom (d) percentage depth dose measurement

Film calibration

The films were cut into two pieces (2 cm × 2 cm) with their orientation clearly labeled and exposed at the depth of Zref for each electron energy for doses ranging from 0 to 6 Gy. The calibration was done in a solid water phantom. An ionization chamber measurement was also done in the same phantom to know the dose delivered to the film pieces. Films were scanned after 24 h using Epson 10000XL (Epson America, Inc., Lay Beach, CA, USA) flatbed scanner as per the manufacturer's scanning protocol. Epson software (Epson America, Inc., Lay Beach, CA, USA) was used for scanning the films in transmission mode at a resolution of 75 dpi with all image enhancements turned off. The images were saved as 48 bit RGB Tagged Image File Format. The ImageJ software (Natural Institute of Health, Bethesda, MD, USA) was used to extract pixel values reading from red channel, which was used to calculate net optical density (OD). The calibration curve was plotted between delivered dose and measured net OD. The uncertainties in PDD measurements with our film dosimetry setup were estimated using the method described by Devic *et al*.[20] and were found ±1.5% overall. The EBFs were calculated as defined previously from the film measured PDD data.

Results

Monte Carlo simulation of linac

Figure 4 shows the comparison of MC simulated PDD and RFA measured PDD for the 6 and 9 MeV electron beams. It is seen that the calculated and the measured PDD values agree well. The average dose error was less than ±2%. Table 1 shows the comparison at clinically relevant points such as the depth of maximum dose (Zmax), depth of 90% of maximum dose (R_{90}), depth of 80% of maximum dose (R_{80}), depth of half of maximum dose (R_{50}), and practical range (Rp). The values shown in the table agree with in ±1 mm further validating our MC model.

Monte Carlo simulation of electron backscatter

The PDD curves obtained from MC simulations for various lead sheet positions and normalized against PDD without lead are shown in Figure 5a and b. From these curves, the EBF values were calculated for each lead sheet position [Table 2]. Figure 6a and b, and Table 2 show that aluminum is able to reduce the backscatter electron at the tissue lead interface, and subsequently, the EBI is reduced in upstream direction. A 25% reduction in electron backscatter was observed when the lead sheet is layered with 2 mm of Al.

Gafchromic film measurements

Gafchromic film measurements were used to verify the accuracy of MC simulations. The central axis PDD was extracted from the film measurements and normalized to the maximum dose value on the regular measured PDD curve. Figure 5a and b show a comparison plot of film measured PDD and MC simulated PDD. The absolute percentage difference was also calculated and shown in the inset of the same figures. It is seen in Figure 5a and b that the film measured and MC predicted PDD agree well (±3%) except near the interface. The EBF values calculated from the MC simulations and film measurement agree within 7% for both the energies. The dose measured by the film near the interface is lower at both the energies. The film measurements also show higher transmission dose beyond the lead shielding. The reason for this disagreement could be the impurity in lead sheets used for experimental measurements. There are not enough lead atoms to provide backscatter electrons as compared to pure lead of 2 mm which was simulated in MC. This might have added to the higher transmission dose also.

Figure 7 shows the plot of upstream electron backscatter from lead shielding placed at 1.5 and 2.0 cm for 6 and 9 MeV,

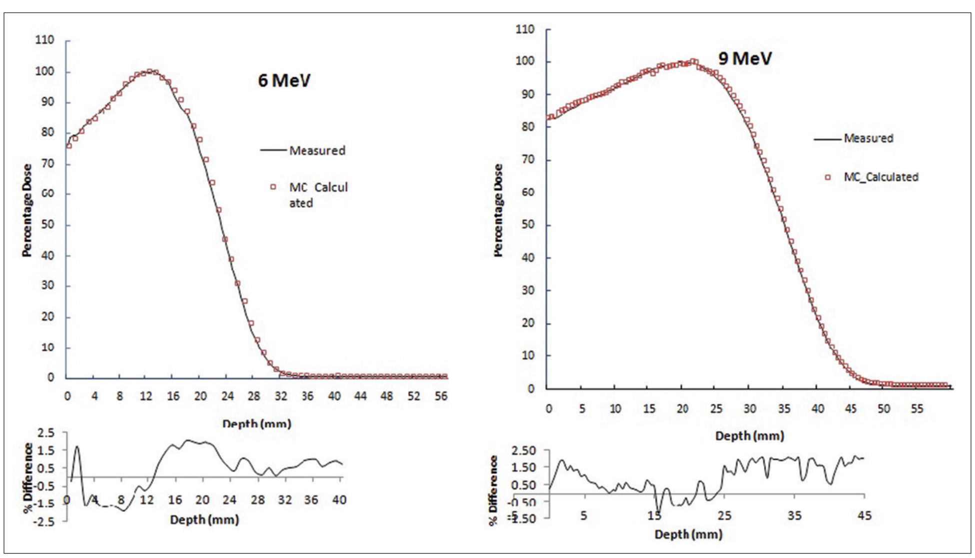

Figure 4: Percentage depth dose comparison between Monte Carlo calculated and water phantom measurements for 6 and 9 MeV electron beams. The percentage difference between the two is shown at the bottom

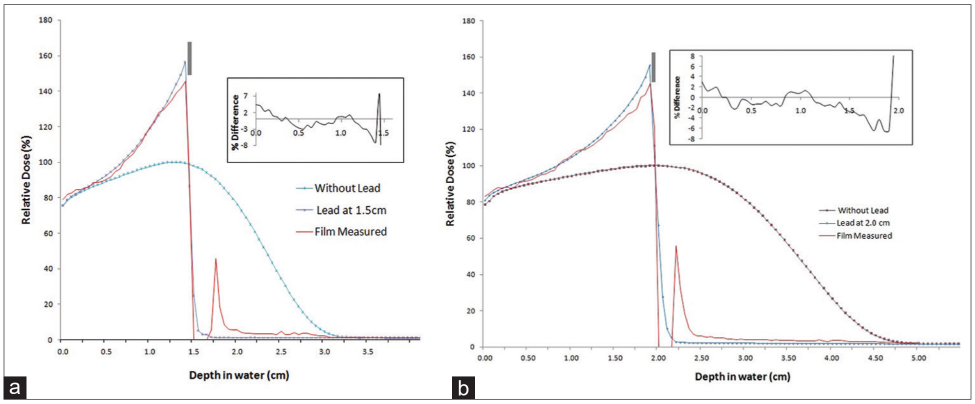

Figure 5: (a) Relative depth dose curves (Monte Carlo simulated and film measured) for 6 MeV electron beam with 2 mm lead shielding placed at the depth of 1.5 cm compared to the standard percentage depth dose without lead. The percentage difference between Monte Carlo simulated and film measured percentage depth dose is shown in inset. (b) Relative depth dose curves (Monte Carlo simulated and film measured) for 9 MeV electron beam with 2 mm lead shielding placed at the depth of 2.0 cm compared to the standard percentage depth dose without lead. The percentage difference between Monte Carlo simulated and film measured percentage depth dose is shown in inset

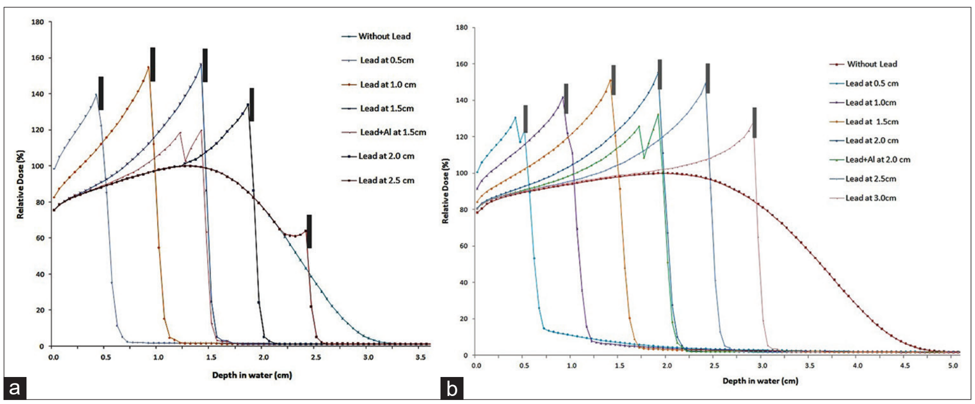

Figure 6: (a) Relative depth dose calculated using Monte Carlo simulations with 2 mm lead shielding placed at depths 0.5, 1.0, 1.5, 2.0, and 2.5 cm for 6 MeV electron beam. Relative dose reduction is seen when a 2 mm aluminum layer is placed over the lead shield at the depth of 1.5 cm.(b) Relative depth dose calculated using Monte Carlo simulations with 2 mm lead shielding placed at depths 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 cm for 9 MeV electron beam. Relative dose reduction is seen when a 2 mm aluminum layer is placed over the lead shield at the depth of 2.0 cm

Table 1: Measured and Monte Carlo calculated percentage depth dose parameters and their comparison

Depth of lead shielding (cm)	6 MeV electron beam			9 MeV electron beam		
	EBF MC calculated (with lead only)	EBF MC calculated (with lead + 2 mm aluminum)	Percentage reduction in EBF	EBF MC calculated (with lead only)	EBF MC calculated (with lead + 2 mm aluminum)	Percentage reduction in EBF
0.5	1.36	1.22	10.29	1.17	1.10	5.98
1.0	1.50	1.28	14.66	1.41	1.23	12.76
1.5	1.56	1.19	23.70	1.51	1.28	15.26
2.0	1.36	1.02	25.00	1.55	1.29	16.80
2.5	0.62	-	-	1.49	1.13	24.16
3.0	-	-	-	1.28	1.01	21.10

MC: Monte Carlo, PDD: Percentage depth dose, EBF: Electron backscatter factor

respectively. The maximum ranges of electron backscatter toward phantom surface are 7 and 10 mm for 6 and 9 MeV electron beam, respectively. This range also depends on the depth of shielding placement [Figure 6a and b]. The range of electron backscatter can be considerably reduced by adding the aluminum layer to the lead shielding.

Discussion

Table 2 shows that the EBF values depend on the position (depth) of the shielding for a particular energy. This information is required to decide the thickness of bolus or aluminum sheet needed to minimize the backscatter dose for a specific linear

Table 2: Electron backscatter factor variations with different lead shielding positions and with different lead + aluminum shielding positions

PDD parameter (mm)	6 MeV			9 MeV		
	Measured (mm)	MC calculated (mm)	Difference (mm)	Measured (mm)	MC calculated (mm)	Difference (mm)
Z_{max}	13.20	13.50	0.30	20.50	21.38	0.88
R_{90}	16.60	17.50	0.90	27.00	27.50	0.50
R_{80}	19.07	19.50	0.43	29.20	30.06	0.86
R_{50}	23.06	23.98	0.92	35.14	35.30	0.16
Rp	29.53	30.47	0.94	44.53	45.08	0.55

Z_{max}: Depth of maximum dose, PDD: Percentage depth dose, MC: Monte Carlo, R_{90}: Depth of 90% of maximum dose, R_{80}: Depth of 80% of maximum dose, R_{50}: Depth of half of maximum dose, Rp: Practical range

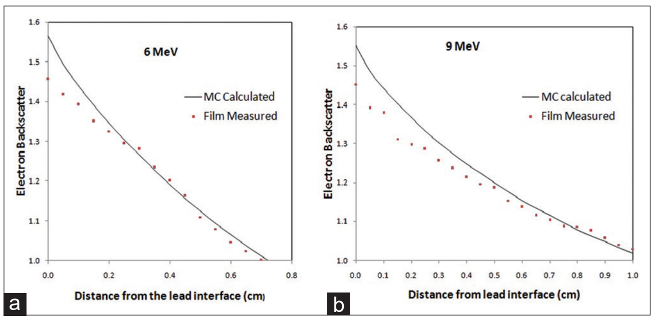

Figure 7: Relative upstream electron backscatter from the lead shielding interface for (a) 6 MeV and (b) 9 MeV electron beams

accelerator model available at our center. Figure 6a and Table 2 show that for the 6 MeV electron beam, the EBF increased from 1.36 to 1.56 in the buildup region and then decreased to 0.62 at the depth of 2.5 cm. In Figure 6b and Table 2, for the 9 MeV electron beam, the EBF increased from 1.17 to the maximum of 1.55 at the depth of 2.0 cm and then decreased to 1.28 when the lead shield was placed at the depth of 3.0 cm. The backscatter contribution reduces to minimal as the depth of shielding approaches to practical range (Rp) of the beam. In Figure 6b, it is seen that 2 mm thick lead is not enough to shield 9 MeV electron beam when the shielding is placed at shallower depths (0.5 and 1.0 cm). However, such a thickness is adequate to provide saturation level of backscattering in the energy range from 4.6 to 33 MeV.[4]

From Table 2, it is observed that at a fixed depth in the buildup region, the EBF decreased with increasing energy. At the depth of 5 mm, the EBFs were 1.36 and 1.17 for 6 and 9 MeV electron energies, respectively. Weaver *et al*. also measured the EBF using Kodak XV films and their values were 1.20 and 1.15 for 6 and 9 MeV electron beams.[3] The difference in result values could be attributed to the changes in electron energy and angular spectra which are specific to each linear accelerator model. In addition, it should be noted that Weaver *et al*. performed their measurements in a polystyrene phantom, whereas ours were performed in water. Various authors[4,11,14,15] have measured and MC simulated the EBF at various energies ranging from 4 to 33 MeV and demonstrated the large variation in the estimated EBF values. However, they all have noted the same trend of decreasing EBF with increasing energy of the electron beam.

In general, a tissue-equivalent bolus is wrapped around the lead shielding to protect the overlying tissue from backscatter dose. Various authors[3,7,21] have suggested that by adding a low atomic number material (aluminum) layer on top of the lead shielding would significantly reduce the backscatter dose. We investigated the efficiency of 2 mm aluminum sheet on top of the lead shielding placed at various depths for two electron beam energies (6 and 9 MeV). Figure 6a and b show the change in PDD when 2 mm aluminum was added to the lead shielding placed at depths of 1.5 and 2.0 cm for 6 and 9 MeV electron energies respectively. It can be seen that aluminum can reduce the backscatter dose by 25% in the upstream to the lead interface. Table 2 shows the calculated EBF with the presence of 2 mm aluminum layer on the top of lead shielding which is placed at different depths in water for both the energies. The percentage reduction in EBF by adding 2 mm aluminum is also shown in Table 2. Table 2 shows that, at a particular depth, the percentage reduction in backscatter is more for 6 MeV as compared to 9 MeV electron beam. This is because at lower beam energy the backscatter electrons are also of lower energy which are predominantly absorbed by the aluminum sheet. For a particular electron beam, the effectiveness of the aluminum layer increases with the depth of shielding placement. The percentage reduction in EBF at 6 MeV energy increases from 10.29% to 25% at depths from 5 to 20 mm, respectively. Similarly, at 9 MeV electron beam, the percentage reduction increases from 5.98% to 24.16% at depths from 5 to 25 mm. As the most practical clinical situations coincide with our experimental situations where 6 or 9 MeV electron beam is used with the shielding placed at the depths (from 1.5 to 2.5 cm), the percentage reduction in EBF is quite significant (23%–25%). A local "minima" at tissue-aluminum interface represent the relative dose profile in buildup region, where incident electron beam travels from low-density (water) medium to high-density (Al) medium. The same is not observed at tissue-lead interface as the incident electrons are almost completely absorbed by lead (high Z) at surface itself.

Conclusions

The electron backscatter contribution with internal shielding was systematically studied for two widely used electron energies 6 and 9 MeV produced from a Varian 2100 Clinac. The MC modeling of the linac was validated with ion chamber-based measurements. Further, the MC calculated EBF values were compared with Gafchromic film based measurements and found to be acceptable except in the close vicinity of the lead interface. This disagreement could be attributed to the impurities in the lead sheet used for the measurements. Ideally, the lead sheets with accurate composition should be MC modeled, but in our case, the vendor could not provide accurate information on quality/composition of lead sheets. Therefore, the experimentally measured data should take precedence over MC simulated in the regions of disagreement.

The effectiveness of a thin aluminum layer on the top of lead shield in reducing the backscatter was also studied. It was found that 2 mm lead shielding is good enough to provide adequate (95%) shielding of normal tissues at 6 and 9 MeV electron beams, except at shallower depths (0.5 and 1.0 cm) for 9 MeV electron beam. This combination of shallow depth and 9 MeV is rarely a clinical situation. A 2 mm aluminum sheet on the top of lead shield was found to be effective in reducing the backscatter toward treatment surface. The aluminum layer was more efficient at lower energy beam. This study can be further extended to generate the EBF data for all the electron energies available with the local linac.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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