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ORIGINAL PAPER

Monte Carlo calculation of scattered radiation from applicators in low energy clinical electron beams

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Abstract. In radiotherapy with electron beams, scattered radiation from an electron applicator influences the dose distribution in the patient. The contribution of this radiation to the patient dose is significant, even in modern accelerators. In most of radiotherapy treatment planning systems, this component is not explicitly included. In addition, the scattered radiation produced by applicators varies based on the applicator design as well as the field size and distance from the applicators. The aim of this study was to calculate the amount of scattered dose contribution from applicators. We also tried to provide an extensive set of calculated data that could be used as input or benchmark data for advanced treatment planning systems that use Monte Carlo algorithms for dose distribution calculations. Electron beams produced by a NEPTUN 10PC medical linac were modeled using the BEAMnrc system. Central axis depth dose curves of the electron beams were measured and calculated, with and without the applicators in place, for different field sizes and energies. The scattered radiation from the applicators was determined by subtracting the central axis depth dose curves obtained without the applicators from that with the applicator. The results of this study indicated that the scattered radiation from the electron applicators of the NEPTUN 10PC is significant and cannot be neglected in advanced treatment planning systems. Furthermore, our results showed that the scattered radiation depends on the field size and decreases almost linearly with depth.

Key words: Monte Carlo • radiation therapy • medical linear accelerator • electron applicator • scattered radiation • treatment planning

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Introduction

Nowadays, electron therapy plays an important role in radiation therapy. The most clinically useful energy range for electrons is 6–20 MeV [18]. At these energies, electron beams can be used for treating superficial tumors with a characteristically sharp drop-off in the dose beyond the tumor [17]. In order to apply an electron beam with well defined edges on the patient surface, it is necessary that the beam is collimated close to the patient surface. Such collimation is frequently achieved by attaching electron beam applicators to the linear accelerator treatment head [9]. A common configuration for such devices is as a concentric series of apertures which act as beam trimmers. Arbitrary field shapes are achieved using customized lead or low melting point alloy (LMPA) cut-outs [7, 23, 24]. The influence of such collimation systems on the machine output and dose distributions has been investigated by several researchers [3, 7, 16, 24, 29]. Empirical and theoretical models of varying complexity for these effects have been presented [5, 8, 19, 22, 23, 31], some concentrating on the effects of field size on the machine output, and some including the effects of applicator scattered particles.

Particles in the electron beams entering the applicator assembly will either pass through to the patient surface without interacting with the applicator components or intercept by the applicator trimmer. Of those which strike a trimmer, most are absorbed through. However, some emerge after a varying degree of scattering and energy loss. Particles emerging from the trimmers will either travel directly to the patient surface, where they will have an altered energy and angular distribution relative to those particles in the primary beam, or enter another trimmer [9]. The effect of the applicator is thus to provide an additional beam component (applicator scatter) to the primary beam which may influence the machine output and resulting dose distributions.

Therefore, scattered radiation from the electron applicators applied in radiotherapy is a well-known phenomenon [30]. It is shown that for the electron applicators applied in the Philips SL75 series (box-type applicators) the dose resulted from the scattered radiation could be as much as 30% of the dose delivered by the direct irradiation of 12 MeV electron beams [30]. In line with the international recommendations made by the ICRU (1984), the currently applied electron applicators of these accelerators have a diaphragm type design [13]. However, the scatter contribution in the dose from electron applicators is significant even in modern accelerators [30]. In commercially available treatment planning systems, the scattered radiation from the electron applicators is not included. For example, the electron algorithm within Pinnacle treatment planning systems is based on the pencil beam approach [10] and in the Cadplan treatment planning systems it is based on the generalized pencil beam approach [4]. This means that the scattered radiation is supposed to deliver an extra dose component with similar characteristics as the dose from the primary electrons, namely the electrons which are not scattered by the electron applicator.

In an attempt to calculate dose to patients more accurately, 3D planning algorithms are developed which require, as the input, the initial phase space data, just below the electron applicator [14, 17, 25]. Such an initial phase space data describes the electron beam, differential in space co-ordinates perpendicular to the beam axis, differential in energy, and differential in solid angle. An initial phase space can be calculated using the BEAM code [26], or by a less computer memory demanding parameterization of the result [20]. In addition, approximate models for the initial phase space have been proposed that are fully based on measurements [15], or on both, measurements and Monte Carlo simulations, for instance the multiple source model [1].

The aim of this study was to investigate and calculate the amount of scattered dose contribution from the diaphragm applicators in low energy clinical electron beams at different field sizes. In addition, the relationships of the scattered dose contributions with the field size and electron beam energy were investigated. The results of this investigation are based on the Monte Carlo method. So, the extensive set of the data provided, could be used as input or benchmark data for Monte Carlo dose calculation algorithms which employ a parameterized initial phase space to characterize the clinical electron beam.

Material and methods

Medical linear accelerator

All experimental measurements and Monte Carlo calculations were performed on a NEPTUN 10PC medical linear accelerator [28]. The accelerator is a stationary wave type equipped with an achromatic bending magnet system. This linac provides a 9 MV photon and three electron beams 6, 8 and 10 MeV on which this investigation was carried out.

Electron applicators

Electron beam applicators are usually used to collimate the beam, and are attached to the treatment unit head such that the electron field is defined at distances as small as 5 cm from the patient [12]. However, when the electron beam applicators of the NEPTUN 10PC linac are attached to the treatment head, there is left no distance between the edge of the electron applicators and the patient surface at 100 cm SSD. Therefore, to maintain the minimum distance of 5 cm between the electron applicators and the patient surface, the SSD is set to 105 cm in clinical practice with the NEPTUN 10PC linac.

The design of electron applicators in different accelerators varies significantly; including the number of applicator scrapers (diaphragms) used to collimate the electron beam and the position of scarpers placed at different distances from the focus. The electron beam applicators of the NEPTUN 10PC linac are variable trimmers consisting of five scrappers. Every scrapper is constructed from 3 layers with different thicknesses and materials. The distances between all the scrapers, except the last one, are the same. In order to achieve a flat dose profile and minimize the patient discomfort and because of the argument mentioned at the beginning of this section, all practical measurements as well as simulated calculations carried out for the electron therapy by this accelerator were performed at a source to surface distance (SSD) equal to 105 cm. The position of the photon beam blocks (jaws) is changed for each field size set by the applicators of this linac depending on the field size chosen. Detailed information regarding the geometry and materials of the applicators used in this study was provided by the vendor.

Accelerator operation

No manufacturer allows irradiation of an electron beam mode without a proper electron applicator in place. A special non clinical mode (service mode) is needed to produce an electron beam without the applicator in place. So, in order to override interlocks generated by the accelerator, we used the service mode of the accelerator for the experimental measurements required at this situation.

Experimental measurements

In this study the central axis depth dose curves were measured in water at SSD = 105 cm using a computerized water phantom (Scanditronix RFA-300[1)]) radiation field analyzer which is a dosimetry system for the 3D radiation field analysis. A waterproof high-doped *p*-type silicon diode (EFD-3G), made by the same manufacturer[1)], was used to measure the percentage depth doses at the central axis. The thickness of this silicon chip is 0.5 mm and its' active area diameter is 2 m. Another diode as the reference detector was placed in the periphery of the radiation field during the experimental measurements. Because the variation of silicon to water stopping power ratio with electron energy is quite minimal (~ 5% between 1 and 20 MeV), measurement made with a diode may be used directly to give depth-dose distributions [18]. The percent depth dose (PDD) curves for 6, 8 and 10 MeV electron beams were measured with and without the applicators in place for three field sizes (3 × 3, 10 × 10, 25 × 25 cm^2) at SSD = 105 cm. In addition, the dose profiles were measured for the reference field at the d_{max} for each electron beam. All the curves are provided from averaged values obtained from three separate measurements made for every situation.

Estimating scatter contribution for the central axis depth dose curves

A relative depth dose curve in water from an electron beam is formed by primary electrons and electrons that have interacted with devices such as scattering foils, monitor chamber, photon beam blocks and electron applicator [2]. The difference occurs in the central axis depth dose curves, generated in the situations in which the applicators are in place from those that are not assumed to give the amount of scattered radiation generated by the applicator. It was also assumed that the backscattered electrons from the electron applicators do not reach the monitor chamber [32]. In the experimental measurements the position of the jaws was the same for both of the conditions, with and without the applicators in place, for every field size. Thus, when the applicators were not in place, the relevant field size was larger at the isocenter distance compared to the other condition. Therefore, because the setting of the photon jaws is not changed, the electron fluence on the central axis, as far as it is not originating from the applicator, is expected to be hardly different whether the applicators be in place or not.

Monte Carlo calculations

Electron beams were modeled using the BEAMnrc system based on the EGSnrc code [27]. For the Monte Carlo simulation of the linac model used in this study (NEPTUN 10PC), detailed information, regarding the geometry and materials used for various components of the treatment head, was provided by the vendor [28]. The geometry of the linac treatment head structure was modeled for three field sizes (3 × 3, 10 × 10 and 25 × 25 cm^2) and three nominal electron beam energies (6, 8 and 10 MeV) at SSD = 105 cm.

All the simulations, made for the electron beam nominal energies, were performed with monoenergetic parallel circular beam sources with a 2 mm diameter incident from the accelerator model. The electron beam energies were adapted to give depth dose curves having the same depth at the 50% dose level. For all the simulations, the energy cut-offs for the particle transport were set to ECUT (electron cut-off energy) = 0.7 MeV (kinetic energy plus rest mass) and PCUT (photon cut-off energy) = 0.01 MeV. The number of source electrons was enough (10^8) histories which led to about 1% relative standard error of the mean of the calculated dose. In this work, particles, after being transported, were scored at a scoring plane placed after the last scraper. Then, the information of this scoring plane, which is named the phasespace file by the code, was used as the source input for the simulations of the dose distributions in water phantoms of a rectilinear voxel geometry configuration using the DOSXYZnrc system being itself based on the EGSnrc Monte Carlo code [33]. The phasespace file contains information about particle type, energy, position, direction, weight, and a tag that records the particle history at any specified plane in the simulation geometry.

Statistical uncertainties of a Monte Carlo simulation can simply be reduced by running more particle histories so that its effect becomes insignificant for a particular application [21]. So, by using 10^8 histories, the statistical uncertainties, obtained by the EGSnrc Monte Carlo simulation code in this study, was estimated to be about 0.3% and 1% for the phasespace parameters and the absorbed dose calculation respectively.

In order to benchmark the simulated models, the PDD curves and dose profiles at d_{max} were measured experimentally for all the energy settings at the reference field size with the diode detectors in the RFA 300 water phantom[1)], as mentioned above, and compared with the calculated values estimated by the Monte Carlo method.

After benchmarking, the simulated machine for the three nominal energies (6, 8 and 10 MeV) at the reference field size, the central axis depth dose curves of the electron beams for the other field sizes were measured and calculated for both conditions of the applicators (with and without the applicators in place). Then, the measured and calculated values of the PDD curves were compared with each other. In order to obtain the scatter contributions from the applicators, the values of the calculated depth doses were normalized to the dose at d_{max} for the condition when the applicators were not in place. Finally, the scattered radiation

[1)] IBA Scanditronix Medical AB, Uppsala, Sweden.

generated by the applicators, for each setting, was determined by subtracting the central axis depth dose curve calculated without the applicators from that with the applicators. In addition, the scatter contributions from the applicators were also calculated by using the LACTH bit characterizations of the BEAMnrc Monte Carlo code.

Normalization of depth dose curves

The nominal energies investigated in this work ranged from 6 to 10 MeV leading somehow to a variation in the penetration of the electron beams. Thus, to provide a clear presentation of the results, the scatter contribution was expressed as a function of the normalized depth, i.e. relative to its practical range d/R_p, thereafter they were normalized to the dose at d_{max} for the situation in which the applicators were not in place.

Results

Figures 1 and 2 show the measured and calculated depth dose curves for the 6, 8, and 10 MeV electron beams in the reference field, 10 × 10 cm^2, with and without the applicators, respectively. Figures 3 and 4 show the cross line dose profiles measured and calculated at the d_{max} for the three electron beam energies at the reference field with and without the applicators, respectively. The figures show very good agreement between the measured and calculated PDD curves as well as the dose profiles.

It must be noted that the experimental measurement made for each point was repeated three times leading to a maximum 0.02 standard error (SE). Comparing this experimental error with 1% relative standard error of the mean of the Monte Carlo calculated values indicates good agreement between the uncertainty level of the Monte Carlo simulation method and the experimental method used in this study. This made us able to compare the calculated Monte Carlo results with the experimental measured values using the Kolmogorov-Smirnov (KS) test.

Table 1 shows the *P*-valves of the KS test resulted from the comparison of the calculated values with the experimental ones. The *P*-values indicate that the PDD values and the dose profiles calculated with the Monte Carlo code and measured experimentally for the three electron beams match well with each other.

As mentioned above, the arithmetic difference between the calculated depth dose curves, with and without the applicators, can be regarded as a measure of the applicator scatter. Figure 5 shows the calculated relative depth dose for the 10 MeV electron beam at the reference field, 10 × 10 cm^2. In this figure the scattered dose contribution is calculated as the arithmetic difference between the two curves. At the depth of the maximum dose (24 mm), d_{max}, the scattered radiation

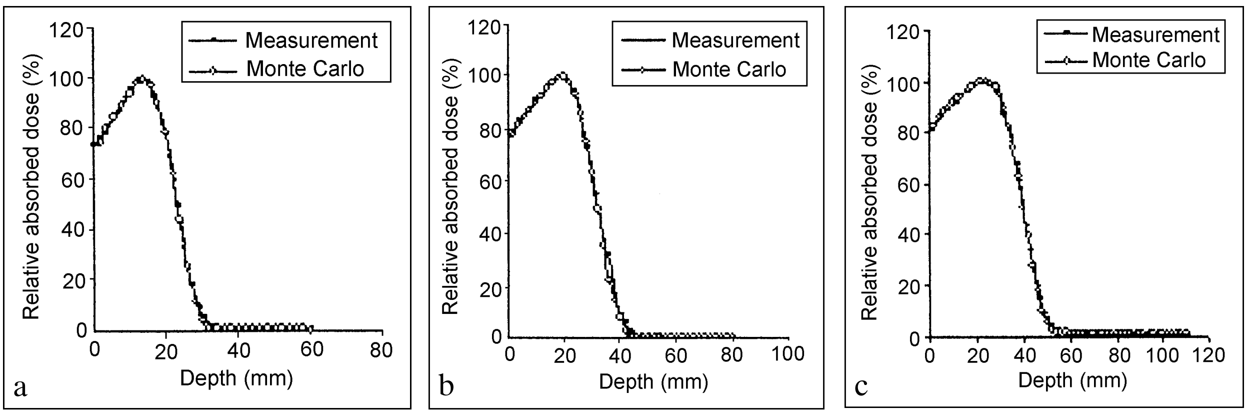

Fig. 1. Central axis percent depth dose curves of the experimental measurements and MC calculations for different electron beam energies: 6 MeV (a), 8 MeV (b) and 10 MeV (c), at the reference field size (10 × 10 cm^2), with applicators.

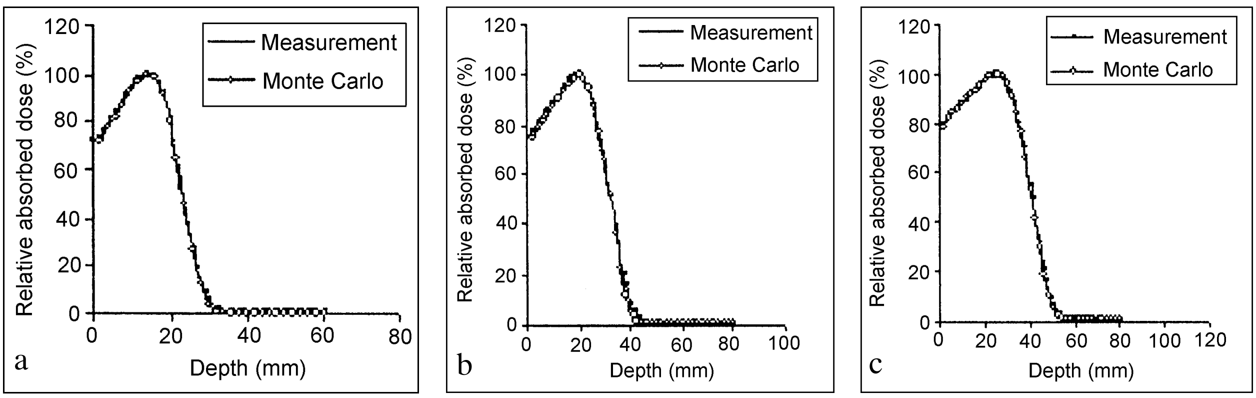

Fig. 2. Central axis percent depth dose curves of the experimental measurements and MC calculations for different electron beam energies: 6 MeV (a), 8 MeV (b) and 10 MeV (c), at the reference field size (10 × 10 cm^2), without applicators.

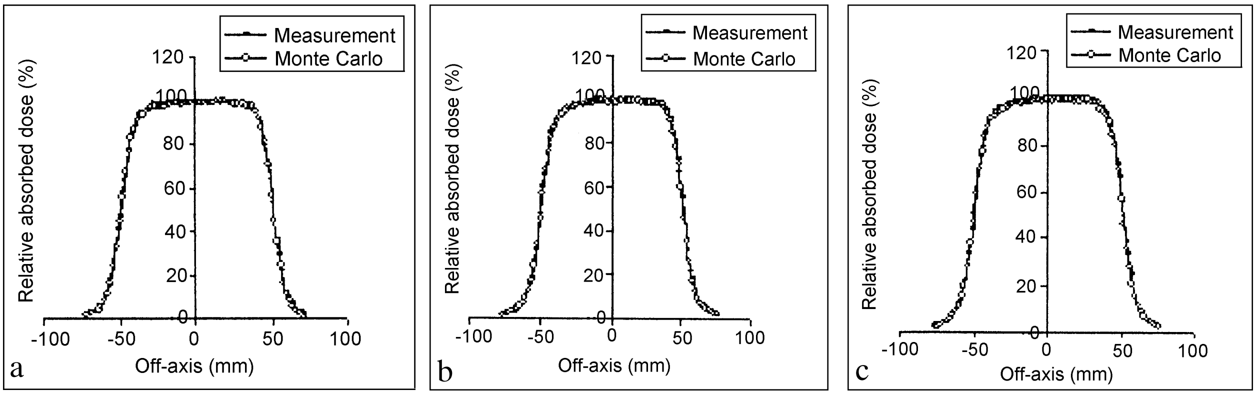

Fig. 3. Cross line profiles of the experimental measurements and MC calculations for different electron beam energies: 6 MeV (a), 8 MeV (b) and 10 MeV (c), at the reference field size (10×10 cm^2), with applicators.

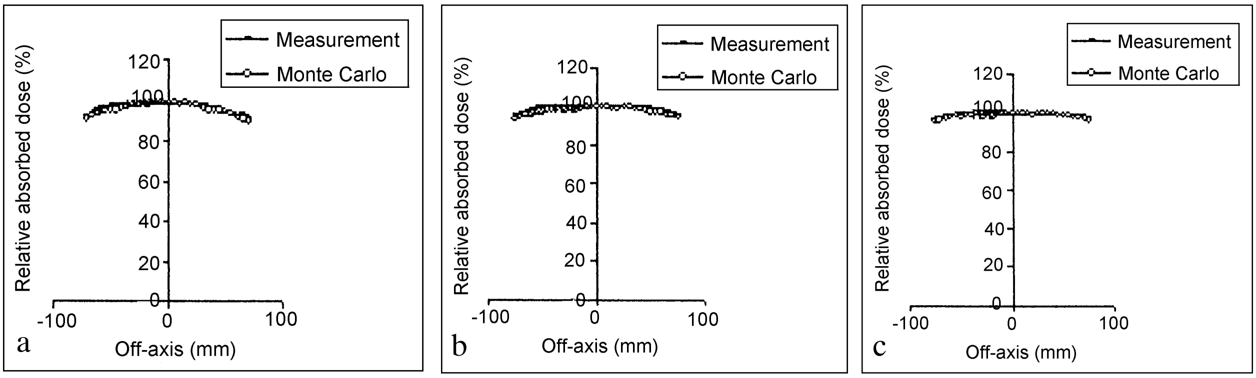

Fig. 4. Cross line profiles of the experimental measurements and MC calculations for different electron beam energies: 6 MeV (a), 8 MeV (b) and 10 MeV (c), at the reference field size (10×10 cm^2), without applicators.

contributes about 8.5% to the percentage of the depth dose, which illustrates the significance of the contribution of the applicators in the scattered dose. Near the surface of the phantom this scattered contribution is even larger (approximately 11%).

Figures 6, 7, and 8 show the calculated applicator scatters in the smallest (3×3 cm^2), the reference, and the largest (25×25 cm^2) field sizes, respectively; for 6, 8, and 10 MeV electron beams.

The scattered dose contributions were also calculated from the LACTH bit characterizations of the BEAMnrc Monte Carlo code. For all the field sizes and electron beams investigated in this study, the scattered radiation from the applicators calculated by the LATCH option of the Monte Carlo code and the differences of the depth dose curves values were in good agreement with each other, with a *P*-value of the KS test being equal to 1.000.

Table 1. The *P*-values of the KS test resulted from the comparison of the experimental measurements and the MC calculations for the reference field size with and without the applicator

Electron beam energy (MeV)	PDD	Dose profiles
With applicator		
6	$P = 0.819$	$P = 0.416$
8	$P = 0.358$	$P = 0.759$
10	$P = 0.346$	$P = 0.769$
Without applicator		
6	$P = 0.415$	$P = 0.782$
8	$P = 0.358$	$P = 0.147$
10	$P = 0.649$	$P = 0.147$

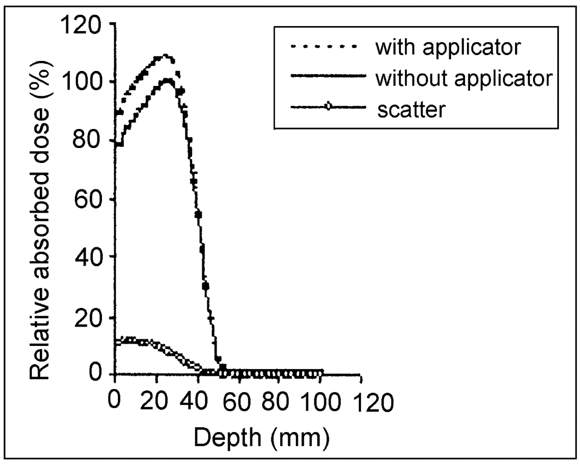

Fig. 5. Calculated relative depth doses for the 10 MeV electron beam at the reference field size. The main dose curve (solid line) is normalized to the maximum central axis dose measured without an applicator. This curve is then subtracted from the relative dose measured with the applicator (dashed line) to calculate the applicator scattered dose contribution (doted line).

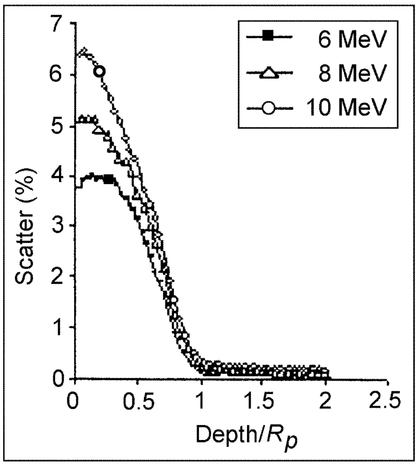

Fig. 6. Calculation scattered radiation from applicators for the smallest field size, 3 × 3 cm^2, for different electron beam energies.

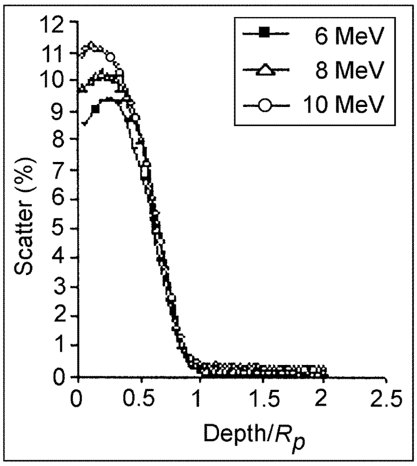

Fig. 7. Calculation scattered radiation from applicators for the reference field size, 10 × 10 cm^2, for different electron beam energies.

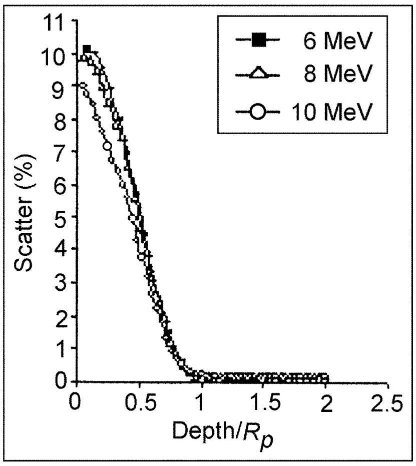

Fig. 8. Calculation scattered radiation from applicators for the largest field size, 25 × 25 cm^2, for different electron beam energies.

Discussion

The Monte Carlo calculations matched well with the measured PDD and does profile curves within 2%. This proves the validity of the Monte Carlo simulation method used for the calculation of the depth dose curves with and without the applicators, as well as the calculated scattered dose distributions due to the applicators at different situations and configurations for which experimental direct measurements may not be practical.

In low energy electron beams (6–10 MeV), investigated in this research, the scattered radiation from the electron beam applicators was ranged from 4 to 11% at the field center and the surface of the phantom. From our results, it can be concluded that the scattered radiation for each beam energy decreases almost linearly with the depth (d/R_p). In addition, in the large field size the contribution of the scattered radiation at the central beam axis is less than the reference field, 10 × 10 cm^2.

The magnitude of the scattered radiation and its dependence on the beam energy and the field size is complex. We expected more scattered radiation at higher beam energies because of their higher penetration nature. However, because of the energy range limitation of the electron beams (6–10 MeV), investigated in this study, that expectation was not proved to be statistically significant. More investigations on higher energy electron beams, up to 20 MeV, may prove this.

We expected less scatter for larger field sizes, because it seems that the amount of the scatter be proportional to the applicator circumference and also the scattered radiation be distributed uniformly over the aperture. But, in practice, the amount of scatter is influenced by the actual design of each applicator in combination with the jaw settings [19]. Changing the jaw position will affect the output by no more than a few percent and is quite insensitive over the range of a few centimeters. As a result, it is difficult to predict the amount of scattered radiation. This is in line with the extensive modeling that is required to model an initial phase space [15] and also beam output (in units of cGy/MU) for various accelerators, beam energies, applicator and insert sizes and distances to phantom [6].

The estimated scatter contribution of the NEPTUN 10PC is somewhat higher than the other accelerators for the same field size and energy [30]. Apparently, changes in the design of the applicators and the collimator head can lead to a higher effective initial angular variance.

For the NEPTUN 10PC linac, investigated in this research, the scattered radiation from the applicators was significantly larger than that measured in the past on a CGR Sagittaire accelerator with a scanning beam [11]. So it may be wise enough to suggest that the scattered radiation of recent type accelerators should be included in the radiotherapy planning procedures to reach an adequate level of accuracy.

Conclusions

The results of this study indicated that the scattered radiation from the electron applicators of the NEPTUN 10PC linac is significant and cannot be neglected in advanced treatment planning systems. Furthermore, our results showed that the scattered radiation of this linac depends on the field size and decreases almost linearly with depth. The data provided by this study could also be used as the input or benchmark data for the Monte Carlo dose calculation algorithms in which a parameterized initial phase space is employed to characterize clinical electron beams.

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