Physics and Imaging in Radiation Oncology 10 (2019) 25–28

Contents lists available at ScienceDirect

Physics and Imaging in Radiation Oncology

journal homepage: www.elsevier.com/locate/phro

Short Communication

Modification of the 4 MeV electron beam from a linear accelerator for irradiation of small superficial skin tumors

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ARTICLE INFO

Keywords:
Electron beam
Energy degrader
Beam modification
Skin tumor

ABSTRACT

Uniform dose distribution with steep lateral gradient within depth range of 0–0.5 cm is crucial to be able to treat small skin lesions. The standard nominal 4 MeV electron beam from Elekta Versa HD linear accelerator was modified with degrading filter to remove the lateral scatter from treatment head and minimize the penumbra. The energy degrading method was verified based on dosimetric properties and output factors (OFs) with comparison of four types of measurement methods. The properties of degraded 4 MeV electron beam and developed electron applicators seem optimal for treating small targets near the skin surface.

1. Introduction

Small superficial non-melanotic skin tumors were traditionally among the first curative indications of radiation therapy (RT). As the incidence of basal cell and spinocellular carcinoma is rapidly increasing in the Western countries [1], RT is still widely used even though the awareness of long-term consequences has increased. Especially in the facial area where the surgical procedures are challenging, and among the elderly people, RT has its place [2].

The most optimal radiation modality for treating superficial tumors with less than 0.5 cm invasion depth, would produce uniform dose distribution, easy protection of adjacent healthy structures, narrow penumbra, insensitivity to moderate density variations or complex surface geometry, and fast dose fall-off for areas deeper than 0.5 cm. The potential techniques include: X-ray contact therapy devices with tube voltage ≤ 50 kV, orthovoltage devices with tube voltage ≥ 150 kV, electron beams from the linear accelerators, superficial brachytherapy applicators with Ir-192 afterloaders, and radioactive superficial molds, like Re-188 paste [3–5]. None of the existing techniques includes all the optimal treatment features.

One possible approach to combine the ideal treatment beam properties for superficial targets has been the use of low-density degrading filters with electron beam. This approach has been used in intraoperative radiation therapy (IORT) where typically a set of circular plexiglas or metal collimators are constructed either for the standard linac or a dedicated IORT device [6]. The introduction of the filters changes the beam characteristics compared to standard electron beam. The degraded beam contains scattered electrons from the filter, which results wider energy spectrum and energy distribution of electrons at the skin surface. To be able to reach acceptable field homogeneity the beam output must be compromised [7,8].

The aim of this work was to develop a method to produce uniform dose distribution within the depth range 0–0.5 cm and as fast dose fall-off as possible in deeper areas. Our approach was to utilize the standard nominal 4 MeV electron beam from the linear accelerator with the beam degrading filter to reduce the energy of about 1.2 MeV. The lateral uniformity was controlled with the extra collimation brought close to the skin surface. After developed an applicator type that fulfilled basic requirements the dose distribution data was collected for treatment planning and patient safety aspects. Comparative absolute dose measurements were performed using four independent methods.

2. Material and methods

2.1. Design of the applicator

The modifications were designed to fit into the structure of the standard square $6 \times 6\ \text{cm}^2$ electron applicator from the Elekta Versa HD (Elekta AB, Stockholm, Sweden) linear accelerator with minimal changes and increase of weight. The lowest electron energy ($R_{50\text{ion}} = 1.7$ cm for the $20 \times 20\ \text{cm}^2$ field size, nominal energy 4 MeV) was degraded with a 0.6 cm thick Plexiglas (polymethyl methacrylate, PMMA) plate located in the second aperture plate. To restrict lateral electron scatter from the plate, an additional 5 cm long PMMA

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https://doi.org/10.1016/j.phro.2019.04.003
Received 16 March 2019; Received in revised form 3 April 2019; Accepted 9 April 2019
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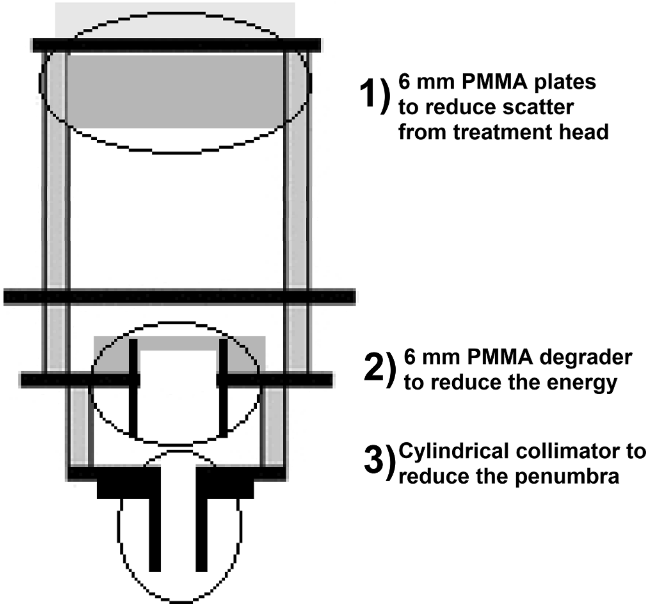

Fig. 1. Modifications of the standard 6 × 6 cm^2 applicator marked with three ellipses from up to down: (1) 6 mm thick PMMA plates restrict lateral scatter from the treatment head, (2) 6 mm thick PMMA degrader was located on the second lowest applicator trimmer level to reduce electron energy, and (3) cylindrical collimators were attached to the standard block holder level.

collimator was added under the degrader (Fig. 1). PMMA material was chosen to minimize bremsstrahlung production.

To minimize the penumbra in the treatment fields, 6 cm long circular PMMA collimators with the inner diameters 2.5, 3, 4 and 5 cm were attached to 1 cm thick brass baseplates. These collimators fit into the standard holder of Wood metal cutouts and the existing coding system was available for collimator size verification. The length of the collimators was set to leave 1 cm space between the skin and the collimator end at the standard treatment distance of 100 cm. The wall thickness of PMMA tubes was 0.3–0.4 cm depending on the diameter.

The dose rate of the degraded beam was reduced, because of the filter. The laterally scattered radiation component through the applicator open sides becomes potentially significant. The lateral dose profiles at 0.2 cm depth, in water up to 30 cm from the beam axis, were measured during the initial testing for the applicator design. A 10–15% dose component was observed at distances > 15 cm from the central axis (CAX). It was found geometrically that the dose component was due to the lateral scatter from the open aperture of the secondary collimators visible through the open sides of the applicator, observed far outside the primary field. This component can be eliminated by adding 0.5 cm thick and 10 cm high PMMA plates surrounding the upper part of the applicator (Fig. 1).

2.2. Dose distributions of circular fields

Beam data for delivering therapeutical dose in a single field at the specified depth was collected with a Sun Nuclear (Sun Nuclear Corp., Melbourne, Florida, USA) non-shielded SunPoint electron diode in the PTW water phantom. The beam data included depth dose curves at the CAX, lateral profiles at several depths (0.2, 0.5, 1 and 2 cm) and output factors (OFs) relative to the standard 20 × 20 cm^2 field with nominal 4 MeV as a reference. Measurements were performed with the nominal treatment distance 100 cm and at an increased distance up to 104 cm. Shielding properties of the whole modified applicator were measured. The measurement covered area up to 30 cm laterally from the beam CAX.

CAX depth dose and the OFs were measured with the small parallel plate ionization chamber (IC) PTW 23342 (0.02 cm^3) (PTW- Freiburg, Freiburg, Germany) in CIRS (CIRS Inc, Norfolk, Virginia, USA) Plastic water solid phantom with a resolution of 0.1 cm. CIRS Plastic water has been shown to be water-equivalent at low-energy electron beams for beam qualities $R_{50} < 4\ g/cm^2$ (E_0 below 10 MeV) [9,10]. For comparison absolute measurements and OF were checked with Gafchromic® EBT3 (International Specialty Products Inc., Wayne, NJ, USA) radiochromic film calibrated with 4 MeV standard electron beam at the depth of dose maximum in CIRS Plastic water.

2.3. Comparative measurements for absolute dose

The lowest electron energy supported by the International Atomic Energy Agency (IAEA) TRS 398 dosimetry standard [11] is $R_{50ion} = 1.0$ cm corresponding approximately to the mean electron energy of 2.3 MeV (≈ 2.33 MeV/cm·R_{50ion}) at the phantom surface. The absolute output of the modified beam was measured using the standard 4 MeV electron beam as a reference. Corrections for temperature, pressure, recombination and polarization were performed. The small degraded beam output D_{deg} was measured with a small parallel plate IC PTW 23342 in CIRS Plastic water. The reference result was acquired from measurement at the IAEA TRS 398 reference depth $z_{ref} = 0.8$ cm for the 20 × 20 cm^2 standard 4 MeV field measured with IC PTW Roos with collected charge m_{ref}, beam quality $R_{50ion,ref}$ and reference dose D_{ref}. In order to take into account the effect of change of water/air stopping power ratio in beam degradation the charge signal for the degraded beam (collected charge m_{deg}, beam quality $R_{50ion,deg}$) was corrected with the relative change of stopping power ratios in water/air, polarization k_{pol}, recombination k_s and measurement $m_{deg,}$ which was performed at the corresponding $z_{ref} = 0.5$ cm. The degraded beam output D_{deg} is given by the equation

$$D_{deg} = \frac{[S_a^w]_{deg}}{[S_a^w]_{ref}} \frac{k_{pol,deg}}{k_{pol,ref}} \frac{k_{s,deg}}{k_{s,ref}} \frac{m_{deg}}{m_{ref}} D_{ref} \tag{1}$$

These results were compared to Sun Nuclear electron diode measurements and Gafchromic® EBT3 film irradiations at same depths to 4 Gy dose which was calculated from IC measurements (Eq. (1)). The diode measurement was done in water and the films were irradiated in CIRS plastic water at d_{max} of corresponding beams. No corrections for diode or film readings were applied, except normalization to reference dose with the non-degraded 4 MeV beam. For the absolute OF definition, the OFs from the IC, diode and Gafchromic® film measurements were analyzed with 10 × 10 cm^2 4 MeV electron field as a reference, because the field was possible to measure with both ICs PTW Roos and 23342, and this made it possible to set the field OF to value 1.

As a totally independent set of measurements irradiations using optically stimulated luminescence dosimeters (OSLDs) from IROC (Imaging and Radiation Oncology Core at MD Anderson Cancer Center, Houston, TX, USA) were performed. OSLDs were irradiated to calculated dose of 1 Gy with 4 MeV standard, degraded and both degraded and collimated (2.5 cm circle) electron fields. Irradiations were performed at the depth of dose maximum ($= z_{ref}$) in the PMMA dosimeter blocks of IROC where the detectors had been placed at the 0.7 cm depth. For the standard 4 MeV with $d_{max} = 0.8$ cm, an extra 0.3 cm layer of CIRS plastic water was used. OSDLs have been calibrated by IROC using their standard procedure and American Association of Physicists in Medicine (AAPM) TG51 dosimetry protocol for electrons [12].

3. Results

The depth dose curves of 4 MeV electrons shown in the Fig. 2A are from two different linac vendors, the degraded 4 MeV beam, one modern orthovoltage device and from the idealized model, where the depth dose curve remains constant and falls instantly to zero, when

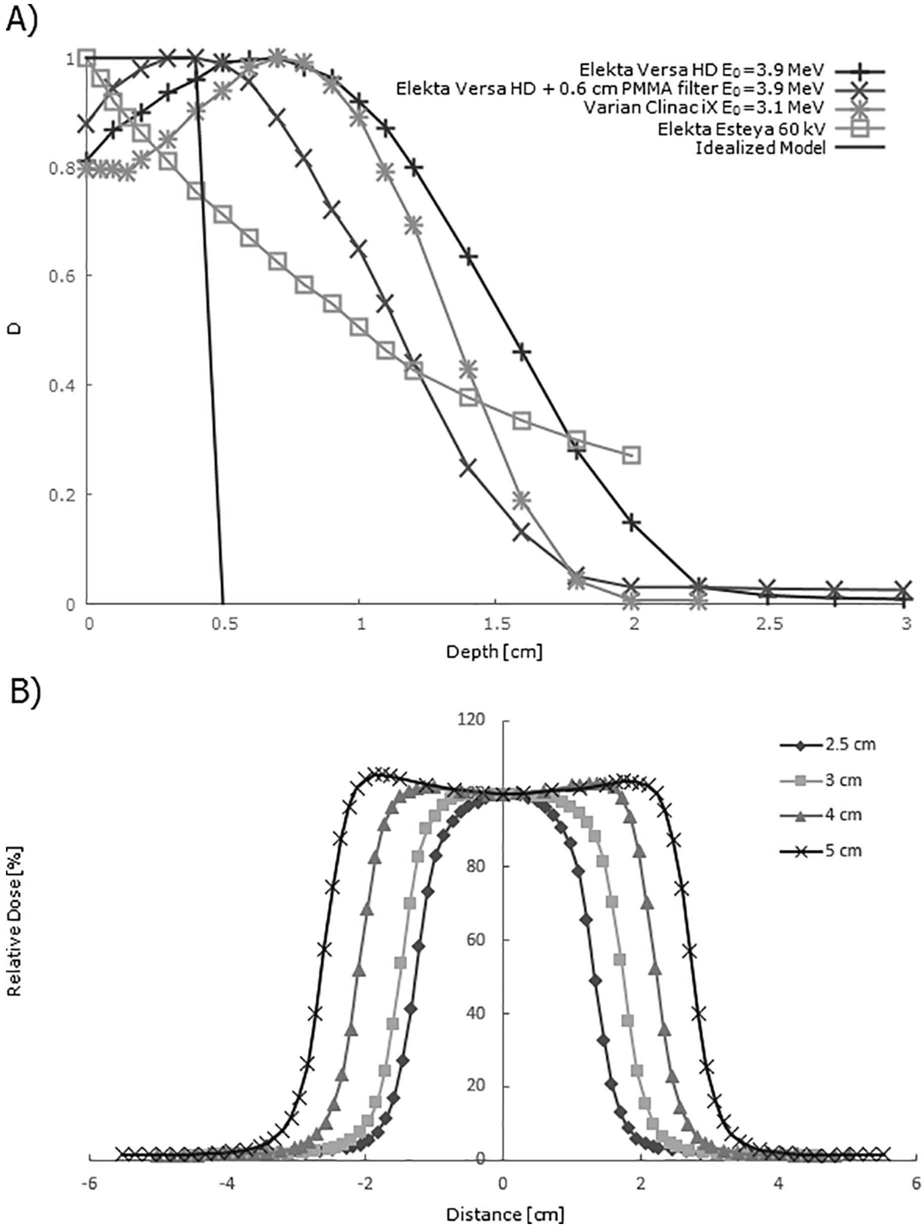

Fig. 2. Depth dose curve and profiles for 4 MeV degraded electron beam: (A) Comparison between depth dose curves. The idealized depth dose model is presented as a solid line. (B) Profiles for different collimator sizes at depth 0.5 cm.

0.5 cm depth is reached. It was noticeable that Versa HD degraded 4 MeV electron beam had shortest build-up region and the fall-off region started at equal depth as the Elekta Esteya brachy device. Important was that the dose drop was faster with degraded electrons than other devices. On average the depth of dose maximum (R_{100}) was 0.46 cm and therapeutic range (R_{80}) 0.86 cm for all collimator sizes. As a conclusion 4 MeV degraded electron beam seemed to reach a compromise between uniform dose distribution to target and healthy tissue protection.

The Fig. 2B shows profiles for all collimator sizes at depth 0.5 cm. The field width of 80% dose from the maximum, a therapeutic field size ($FS_{80\%}$), was 0.2–0.3 cm less than the nominal applicator size except for the largest applicator where it was 0.2 cm larger. Penumbra (20/80) of the 2.5–5 cm collimators were equal, or slightly less than 0.5 cm for all applicators, 0.46–0.50 cm.

The differences in OFs from the IC, diode and Gafchromic® film measurements were found to be smaller than 4%. The difference was the biggest in 2.5 cm collimator field, for other degraded fields the differences were equal or smaller than 2%. The output factors reduced significantly relative to standard 10 × 10 cm 4 MeV open field (OF = 1.000). As an example, for the 2.5 cm collimator field the OFs was only 0.127 (measured with IC) which means drop of factor 8 in output due to strong lateral scatter in the degrader plate. The drop of output was equal to factor of 7–8 for other field sizes. For OSLDs the difference between OFs in reference field size was 8% and in 2.5 cm collimator field 16.5% when compared to IC measurement. The bigger differences in OSLD OFs can be explained by the different medium and the difficulties to determine the correct field size and calibration factors for OSLDs. There may be self-attenuation, because aluminum oxide density is relatively high.

4. Discussion

The properties of developed electron applicators seem optimal for treating maximally 0.5 cm thick skin lesions. Because the properties of standard electron beam were remarkably modified, safety issues become an important role. There is only the block coding system to prevent mixing standard electron shields with the modified applicators. Situation is critical as there is a drop by a factor of 7–8 in beam output due to the distance of PMMA filter from the skin and the scatter out of the field. We consider restricting the use of the 4 MeV beam energy with 6 × 6 applicator for only this specific application to avoid errors.

The modifications were based on the dimensions of the standard applicator. Our aim was to make as minimal changes to achieve satisfactory output. At least two variables could be optimized: size and distance of the degrader plate. Karolis et al. [7] found that degrader plates placed at the jaw face provide better beam homogeneity and steeper penumbra and are to be preferred for that reason, but also relative X-ray contamination increases, as noticed. In conclusion, this study showed that the properties of the degraded 4MeV electron beam and developed electron applicators seem optimal for treating small targets near the skin surface.

Conflict of interest

Assi Valve has received research grant from Helsinki Cancer Center. Other authors have no conflict of interest.

References

[1] Guideline on the Treatment of Basal Cell Carcinoma. Guideline subcommittee of the European Dermatology Forum: Zürich, Switzerland; 2012.
[2] Manyam BV, Joshi N, Koyhman SA. A review of the role of external-beam radiation therapy in nonmelanomatous skin cancer. Appl Rad Oncol 2017;6:6–10.
[3] Lovett RD, Perez CA, Shapiro SJ, Garcia DM. External irradiation of epithelial skin cancer. Int J Radiat Oncol Biol Phys 1990;19:235–42.
[4] Skowronek J. Brachytherapy in the treatment of skin cancer: an overview. Postepy Dermatol Alergol 2015;32:362–7.
[5] Cipriani C, Frisch B, Scheidhauer K, Desantis M. Personalized high-dose-rate brachytherapy with non-sealed rhenium-188 in non-melanoma skin cancer. Int J Nucl Med Res 2017:114–22.
[6] Kasper ME, Chaudhary AA. Novel treatment options for nonmelanoma skin cancer: focus on electronic brachytherapy. Med Devices (Auckl) 2015:493–502.
[7] Karolis C, Wongse-Ek C, Stewart R. Electron beam energy degradation by low density scattering material. Radiat Oncol Biol Phys 1981;7:371–8.
[8] Björk P, Nilsson P, Knöös T. Dosimetry characteristics of degraded electron beams investigated by Monte Carlo calculations in a setup for intraoperative radiation theprapy. Phys Med Biol 2002;47:239–56.
[9] Thomadsen B, Constantinou C, Ho A. Evaluation of water-equivalent plastics as phantom material for electron-beam dosimetry. Med Phys 1995;22:291–6.
[10] Casar B, Zdešar U, Robar V. Evaluation of water equivalency of plastic water^{TM} for high-energy electron beams using IAEA TRS-398 code of practice. Radiol Oncol 2004;38:55–60.
[11] Absorbed Dose Determination in External Beam Radiotherapy: An Internal Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water. IAEA TRS 398. International Atomic Energy Agency (IAEA): Vienna, Austria; 2000.
[12] Almond PR, Biggs PJ, Coursey BM, Hanson WF, Huq MS, Nath R, et al. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. Med Phys 1999;26:1847–70.