Original paper

Dosimetric characteristics of a new unit for electronic skin brachytherapy

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Abstract

Purpose: Brachytherapy with radioactive high dose rate (HDR) [192]Ir source is applied to small skin cancer lesions, using surface applicators, i.e. Leipzig or Valencia type. New developments in the field of radiotherapy for skin cancer include electronic brachytherapy. This technique involves the placement of an HDR X-ray source close to the skin, therefore combining the benefits of brachytherapy with the reduced shielding requirements and targeted energy of low energy X-rays. Recently, the Esteya® Electronic Brachytherapy System (Esteya EBS, Elekta AB-Nucletron, Stockholm, Sweden) has been developed specifically for HDR brachytherapy treatment of surface lesions. The system provides radionuclide free HDR brachytherapy by means of a small 69.5 kV X-ray source. The purpose of this study is to obtain the dosimetric characterization required for clinical implementation, providing the detailed methodology to perform the commissioning.

Material and methods: Flatness, symmetry and penumbra, percentage of depth dose (PDD), kV stability, HVL, output, spectrum, linearity, and leakage have been evaluated for a set of applicators (from 10 mm to 30 mm in diameter).

Results: Flatness and symmetry resulted better than 5% with around 1 mm of penumbra. The depth dose gradient is about 7%/mm. A kV value of 68.4 ± 1.0 kV ($k = 1$) was obtained, in good agreement with manufacturer data (69.5 kV). HVL was 1.85 mm Al. Dose rate for a typical 6 Gy to 7 Gy prescription resulted about 3.3 Gy/min and the leakage value was < 100 μGy/min.

Conclusions: The new Esteya® Electronic Brachytherapy System presents excellent flatness and penumbra as with the Valencia applicator case, combined with an improved PDD, allowing treatment of lesions of up to a depth of 5 mm in combination with reduced treatment duration. The Esteya unit allows HDR brachytherapy superficial treatment within a minimally shielded environment due its low energy.

Purpose

Brachytherapy is a radiotherapy modality where a radiation source (a radionuclide or X-ray unit) is placed inside, or close to, the area that requires a treatment. Brachytherapy is widely used for the treatment of skin cancer [1]. Practical advantages of brachytherapy, especially in small superficial lesions, come from its high accuracy and efficiency as a result of dosimetric and set-up aspects. Accurate positioning of radiation source, sharp penumbra, and quick dose fall-off are some of the key benefits of brachytherapy.

Electron beam radiotherapy, which is also often used for skin cancer treatment, requires the use of cut-outs, bolus and collimation, and needs much more time for dosimetric calculations, preparation/verification and treatment delivery. Templates and cut-outs can be time consuming to create and cumbersome to use, since the percentage of depth dose (PDD) and output change according to the specific treatment conditions. Additionally, these customized devices may increase the chance of an error during set-up.

In case of small skin cancer lesions, brachytherapy with a radioactive high dose rate (HDR) [192]Ir source is often applied, specially using surface applicators, i.e. Leipzig or Valencia type from Elekta (Elekta AB-Nucletron, Stockholm, Sweden). These applicators allow collimation of the radiation to the area of interest, thereby providing an extremely conformal therapy without unnecessary irradiation of normal healthy tissue. The use of these applicators is limited to flat surfaces and treatment areas up to 3-4.5 cm in diameter. Typical prescription depth with these applicators is between 3 mm and 4 mm. Clini-

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cal implementation and dosimetry of skin applicators have been reported elsewhere in the literature [2-10].

New developments in the field of radiotherapy for skin cancer include the introduction of electronic brachytherapy. It involves the placement of an HDR X-ray source positioned directly into skin applicators, combining the benefits of brachytherapy with reduced shielding requirements and targeted energy of low energy X-rays. This offers even more refined approach for skin cancer treatment and further improves conformity of radiation dose to the skin lesion, while sparing surrounding healthy tissues.

Evans *et al.* [11] made the performance assessment of the Gulmay D3300 kilovoltage (combined superficial and orthovoltage) X-ray therapy unit presenting the key dosimetric beam parameters required for routine patient treatment. Beam half-value layers, the applicator, system interlocks, and dose monitor performance were found to be satisfactory. The difficulties of obtaining percentage of depth dose measurements were discussed.

Jurado *et al.* [12] evaluated the Therapax SXT 150 unit, which encompass both low and medium-energy beams. The timer error was significant for all filters and should be taken into consideration for absorbed dose rate determination under reference conditions, as well as for the calculation of treatment times. They recommended PDD measurements for each filter–applicator combination. Beam profiles had small penumbras, good symmetry and flatness, except for the lowest energy beam, for which a heel effect was observed. They conclude that the output factor definition of the IAEA TRS-398 protocol for medium-energy X-ray qualities involves the use of data that is difficult to measure.

The model S700 Axxent™ X-Ray Source (Xoft Inc., San Jose, CA, USA) for electronic brachytherapy was studied by Rivard [13]. This source exhibited depth dose behavior similar to low-energy photon-emitting low dose rate sources ^{125}I and ^{103}Pd, yet with capability for variable and much higher dose rates, and subsequently adjustable penetration possibilities. Liu *et al.* [14] performed the spectral and attenuation curve measurements to characterize it in terms of spectrum and half-value layers. The change in beam quality due to source to source variation and source aging is significant, and each source should be treated on individual basis. Geant4 simulations of the complete X-ray tube in the forward direction yield photon spectra comparable to measured spectra with HVLs matching within uncertainty. However, simulations of the beam in the 90° direction did not match experiments. The cause for the discrepancy remains unknown. Rong and Welsh [15] provided comprehensive calibration procedures for medical physicists in using the Xoft eBx system and skin applicators.

The Emerging Technology Committee of the American Society for Therapeutic Radiology and Oncology (ASTRO) appointed a Task Group within its Evaluation Subcommittee to evaluate new electronic brachytherapy methods that are being developed for (or are already in) clinical use [16]. The Task Group evaluated two devices, the Axxent Electronic Brachytherapy System by Xoft Inc. (San Jose, CA, USA), and the Intrabeam Photon Radiosurgery Device by Carl Zeiss Surgical (Oberkochen, Germany). These devices are designed to deliver electronically generated radiation, and because of their relatively low energy output, they do not fall under existing regulatory scrutiny of radioactive sources that are used for conventional radionuclide-based brachytherapy. This report provides a descriptive overview of the technologies, current and future projected applications, comparison of competing technologies, potential impact, and potential safety issues.

Recently, the Esteya® Electronic Brachytherapy System (Esteya EBS, Elekta AB-Nucletron, Stockholm, Sweden) has been developed specifically for HDR brachytherapy treatment of skin lesions. The system provides radionuclide-free HDR brachytherapy by using a miniature 69.5 kV X-ray source. The purpose of this study is to obtain the dosimetric characterization required for clinical implementation, providing the detailed methodology to perform the commissioning.

Material and methods

Esteya® Electronic Brachytherapy System description

The Esteya® Electronic Brachytherapy System consists of a treatment unit with surface applicators, a user interface with planning software and a treatment control panel. The Esteya system was designed to obtain dose distributions to the skin surface similar to the dose distributions obtained with the Nucletron Valencia Applicator, a shielded applicator placed directly on the skin surface that, in combination with an ^{192}Ir afterloader, provides a focused and uniform dose to surface lesions.

The Esteya treatment unit is portable with four swiveling wheels and an adjustable positioning arm that ease both alignment, and positioning of the X-ray applicator on the patient (Fig. 1). The treatment unit contains the X-ray source, associated surface applicator and applicator plastic cap. The treatment unit displays a light field for accurate positioning. The nominal source to surface distance (SSD) is 6 cm.

A set of five surface applicators can be used to modify the size of the X-ray field: 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm diameter. A clean and (if required) disinfected or sterilized plastic cap is attached to the surface applicator to prevent potential cross-contamination between patients. The surface applicator with plastic applicator cap is placed on the patient skin. There is a special fine tuning mechanism to accurately fit the applicator to the patient surface. The electronic brachytherapy system has a Quality Assurance Device, which provides reproducible daily quality checks (output, flatness and PDD constancy) of the X-ray source and system configuration.

The electronic brachytherapy system has a self-test to check the software and hardware configuration. Carrying out a treatment delivery is possible only when all checks of the self-test have passed successfully, treatment is inhibited if a single check fails. The oil cooling system maintains the temperature of the outside of the X-ray tube, which can be in contact with the patient, below 41°C. The system controllers associated software checks

that the correct surface applicator is installed before radiation therapy is initiated. This software controls the fraction delivery parameters, such as treatment duration and dose rate. The X-ray source voltage has a fixed nominal value of 69.5 kV. The default current is 1.6 mA, which is automatically adjusted to 1.0 mA for fractions smaller than 4 Gy, and to 0.5 mA for fractions smaller than 2 Gy to keep the fraction duration relatively constant and less dependent of the fraction dose. An aluminum flattening filter of 1.6 mm thick is used to generate a maximum nominal dose rate at zero depth of 3.3 Gy/min with a flattened dose profile on the skin.

The computer contains the software for patient administration, treatment planning, treatment delivery, user management, and quality assurance. A treatment planning application is included in the system: after dose per fraction, depth and applicator size are selected, the system presents automatically the required treatment time. It is computed from manufacturer tables of PDD and output. The hard wired control panel is used to start, interrupt and stop a treatment.

Flatness and symmetry evaluation

Flatness, symmetry and penumbra of all available Esteya surface applicator sizes were evaluated using GafChromic® EBT2 radiochromic films (Grafchromic, ISP, USA) and the EPSON Expression 10000XL Photo flatbed scanner (Seiko Epson Corp., Nagano-Ken, Japan). A set of three radiochromic films were located at 5 mm depth in plastic water and irradiated for each surface applicator. The depth of 5 mm was selected, because the application of this unit (according to manufacturer specifications) is for depths up to 5 mm. Consequently, the flatness and penumbra were evaluated at this maximum depth. To consider the response linearity, a film calibration curve with the applicable beam quality was obtained.

The digitalization and evaluation processes were made following our clinical routine protocol: films were digitized prior to irradiation, and 24 h after the pre-exposure pixel values were subtracted from the post-exposure ones (in a pixel by pixel process). This background subtraction, performed with home-made software, allowed reducing inaccuracies in scan measurements. All film pieces were scanned in transmission mode four consecutive times at a resolution of 100 dpi and 48 bit color. The final stored image was calculated as the average of those four images.

The IEC 60976 [17] criteria was followed for flatness and symmetry, similar to other radiotherapy treatment units. It was applied to the flattened area of each profile (flatness is defined as 80% of the distance between the two points, where dose takes 50% of the maximum dose; such a distance is larger than the applicator nominal size) were as follow:

$$Flatness = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

where D_{max} and D_{min} are the maximum and minimum dose values measured in the flattened area of each profile.

Fig. 1. The Esteya Electronic Brachytherapy System

$$Symmetry = \max\left[\frac{D(x)}{D(-x)}\right]$$

where $D(x)$ is the dose at point x; x and $-x$ are points within the flattened region, symmetrical with respect to the central axis. Symmetry as defined as being the maximum ratio within the flattened region.

Penumbra regions were quantified for both AB and GT profiles as the distance between points with dose values corresponding to the 80% and 20% of the dose at the profile center.

Depth dose evaluation

To perform relative and absolute dose measurements, a soft X-ray parallel-plate chamber PTW T34013 model (PTW, Freiburg, Germany) was used. As indicated by the manufacturer, the collection volume of the chamber is 0.0053 cm³, the entrance window thickness is 0.03 mm, and the effective diameter is 1.7 mm. Because of its small active area, the chamber would be appropriate to measure field sizes as small as 0.5 cm × 0.5 cm.

Plastic water phantom (Plastic Water Low Range, CIRS, Norfolk, VA, USA) was used. This plastic material has a density of 1.03 g/cm³. The equivalence of this material to liquid water at the energies considered in this work (a spectrum from 11 keV to 70 keV; see below) is 0.9781 [18]. The plate parallel chamber was placed in a specific plastic water slab with a groove to accommodate it, so that the chamber surface is flush to the slab surface. This solid water slab was designed specially to carry out the PDD measurement. Plastic water slabs of different thick-

ness were placed sequentially on top of the chamber, from 0 to 10 mm. Enough solid water slabs were placed below it to ensure full backscatter.

kV stability

To evaluate the accuracy of the nominal kV (indicated by the device's software as 69.5 kV) and the reproducibility of the kV value, the Barracuda multimeter (RTI Electronics AB, Mölndal, Sweden) and its associated software oRTIgo (oRTIgo QA software for Barracuda, Version 6.4C) were used.

The oRTIgo software has a large number of templates for different tests: accuracy, reproducibility, half value layer (HVL) and many more. Theses templates checks several parameters, and in the 'Test setup' it is possible to specify acceptance limits and other parameters for use in the evaluation of accuracy and reproducibility. The Pass/Fail criteria have been defined here.

The Multi-Purpose Detector (MPD) in the Barracuda multimeter is able to measure field sizes less than 3 mm width and low output levels down to approximately 1 µGy/s. Basically, the detector packages consist of four separate electrometer channels connected to the detectors, with 2.7 mm wide active section, and a moveable filter package that contains six different filter combinations.

To evaluate the tube voltage accuracy, the measured kV was compared against the generator set values. The difference between measured and set kVp was calculated. A Test Setup was configured to check the reproducibility of this X-ray system specifying the maximum allowed deviation: the measured kVp must fall within a predefined $n\%$ of the selected kVp. The test failed if any exposure fell outside the average $n\%$. The test also failed if the coefficient of variation (ratio between the standard deviation and the mean) exceeded the value we chose in the Test Setup.

HVL evaluation

HVL measurements were performed according to the AAPM Radiation Therapy Task Group 61 recommendations [19], using the Barracuda system and high purity aluminum slabs (from 0.5 mm to 2 mm in thickness). For this measurement, the smaller available applicator (10 mm in diameter) was used. The set-up follows the TG-61 and TRS-398 [21] recommendations with a source to detect the distance of 56.0 cm, and aluminum-slabs to sense the distance of 50.0 cm. From these measurements, the specific oRTIgo software provides a HVL value. This test requires the Barracuda with the MPD. HVL was calculated using filters on top of the detector. We began with three exposures (without any aluminum filter added) to get the zero-point and to check the consistency of the generator. We added the aluminum filters and recorded the readings. A measurement was made for each thickness and the mean value was used.

There are several detectors inside the MPD and the total filtration is determined from a combination of these signals and the kV value. The software determined the total filtration dynamically, which means that if an extra filtration is added during a measurement, the software notices the change.

As soon as the measured dose was reduced to 50% of the no-filter value, the HVL was calculated. One exposure must be made without filter, and at least one exposure close to either side of the 50% value.

The HVL was computed using the following formula:

$$HVL = T_b ln\left[\frac{2E_a}{E_o}\right] - \frac{T_a ln\left[\frac{2E_b}{E_o}\right]}{ln\left[\frac{E_a}{E_b}\right]} \tag{1}$$

where Eo is the direct exposure reading without test filtration, Ea – exposure reading above 50%, Eb – exposure reading below 50%, Ta – test filtration used when Ea measurement was made, Tb – test filtration used when Eb measurement was made.

The uncertainty in estimating total filtration between 60 kV and 120 kV is (according to the Barracuda manual) ± 10% mm Al or ± 0.3 mm Al ($k = 2$), respectively. In addition, independently of the Ortigo method, a fit of the readings, according to the TG-61 and TRS-398 protocols was done to compare the results.

Absolute dose evaluation

For this evaluation, the PTW parallel-plate chamber T34013 model in combination with the PTW Unidos electrometer on the plastic water phantom was used. Because this chamber is calibrated in absorbed dose to water, $N_{D,W}$, the TRS-398 code of practice for low-energy kV X-rays beams was followed.

The dose rate at the surface (0 mm depth) was determined according to:

$$D_{wQ} = M_Q N_{D,W,Q_o} K_{QQ_o} \tag{2}$$

where M_Q is the reading of the dosimeter with the reference point of the chamber positioned at the reference point z_{ref} (phantom surface) and corrected for temperature and pressure. N_{D,W,Q_o} is the calibration factor in terms of absorbed dose to water for the dosimeter at the reference quality Q_0, and K_{QQ_0} is a chamber-specific factor, which corrects the differences between the reference beam quality Q_0 and the actual beam quality being used Q.

For the PTW parallel-plate chamber T34013 model used in this work, the N_{D,W,Q_o} was 4.887 × 10^9 Gy C^{-1} ± 3.4% ($k = 2$). This factor was obtained from an accredited Laboratory (PTW Laboratory, Braunschweig, Germany). The calibration is traceable to national standards of the PTB Laboratory (Germany).

K_{QQ_0} was obtained from the calibration certificate of the PTW. A set of correction factors (ranging from 0.997 to 1.017) relative to the quality of the calibration (HVL 0.43 mm Al) for a quality range from 0.10 mm to 3.10 mm Al are included.

Finally, dose rate at 0 mm depth has been determined from the ratio between D_{wQ} and the measurement time, which is the nominal time in the system console.
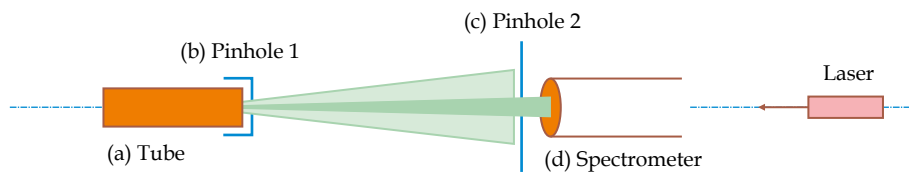
Fig. 2. Schematic view of the spectrum measurement setup

Spectral evaluation

During tube calibration, the output spectrums were measured (PANalytical B.V., Eindhoven, The Netherlands). The measurement setup consists of the following components (Fig. 2): (a) tube with 30 mm diameter surface applicator; (b) lead pinhole, thickness 4.5 mm, opening 4 mm in diameter; (c) lead pinhole, thickness 3 mm, opening 0.7 mm in diameter; (d) germanium crystal spectrometer Ortec GLP 25300/13P4; diameter 25 mm, thickness 13 mm; beryllium window, thickness 0.25 mm; cooled by liquid nitrogen.

All components were aligned with a laser beam, which represents the central axis. The distance from tube to spectrometer was approximately 1 m. Pinhole 1 is used to reduce scatter radiation and was positioned against the tube, pinhole 2 is used to narrow the line of sight of the spectrometer to the central axis and was placed as close as possible to the spectrometer.

The spectrometer was calibrated by putting a piece of solder (lead and tin) in the beam path. The characteristic lines are fitted with their corresponding energies: Pb L-α: 10.550 keV; Pb L-β: 12.612 keV; Sn K-α: 25.191 keV; Sn K-β: 28.481 keV. Also, the endpoint of the energy spectrum 69.5 keV was used. The measurement time of the spectrometer was set to 1000 s. The measured (raw) spectrum was de-convoluted using a Monte Carlo calculated response of the detector. The Penelope2008 Monte Carlo code [20] and the SpekCalc software [22-24] were also used to obtain theoretical spectra to be compared with the measured ones. Penelope2008 is a MC code, which reliability and performance have been widely tested [25]. It employs a mixed procedure to simulate electron and positron interactions (elastic scattering, inelastic scattering and bremsstrahlung emission), in which 'hard' events (i.e. those with deflection angle and/or energy loss larger than pre-selected cut-offs) are simulated in a detailed way, while 'soft' interactions are calculated from multiple scattering approaches. Photon interactions (Rayleigh scattering, Compton scattering, photoelectric effect, and electron-positron pair production) and positron annihilation are simulated in a detailed way.

Penelope2008 cross section data are those of the EPDL97 [26] and EEDL [27], except that for Compton interactions Penelope2008 uses the impulse approximation to account for Doppler broadening, and binding effects in the photon and electron cross-sections.

The X-ray source was modelled according to the characteristics specified by the manufacturer. Source spectra were calculated striking 69.5 keV mono-energetic electrons in the tungsten anode surface to generate X-rays.

The cut-off energy for electrons and photons was considered 1 keV. Spectrum was binned at 0.5 keV intervals. 10^9 electron histories were generated to produce $k = 1$ Type A uncertainties below 1%.

Linearity

As described above, the system changes the intensity according to prescribed dose and depth, in order to reduce the treatment time. To verify the linearity of this conversion, ionization measurements with the T34013 chamber on the plastic water phantom using the 30 mm applicator have been done at different nominal prescribed dose, evaluating the collected charge versus the mA × s settings.

Leakage estimation evaluation

A home-made setup was prepared to enable leakage measurements (Fig. 3). A 3 mm thick lead slab was used to block the primary beam. Leakage was measured at four points at the level of the applicator surface (10 mm applicator, since it is the smallest field size available) and as close as possible to the X-ray tube. Additionally, one extra measurement at a height of 60 mm was also made.

To have a good spatial resolution, the PTW T34013 chamber (the same that was used for absolute dose and PDD measurements) was used. Despite the harder spectrum, we assume that the calibration factor of this chamber is adequate, because of very small resulted value and upper limit obtained. Strictly speaking, due to the harder spectrum, the calibration factor might change. However, since this is an upper limit and the value obtained is very small, we consider that any reasonable modification in the calibration factor will not play a significant role.
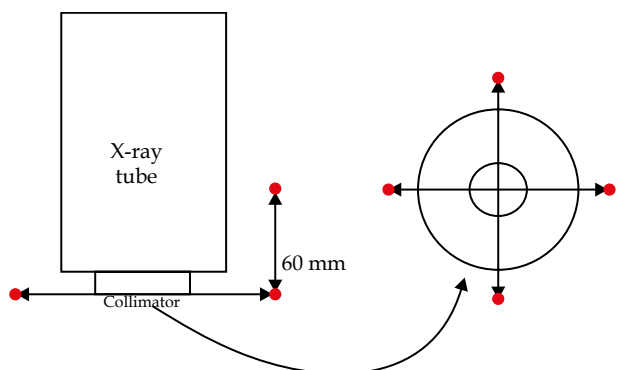

Fig. 3. Schematic representation of the setup for the leakage evaluation

The detected signal for the chamber is very low, so pre-irradiation and post-irradiation chamber leakage were estimated and taken into account to correct the device leakage measurement during irradiation.

Results

Flatness and symmetry evaluation

Table 1 presents the mean flatness and symmetry and Table 2 shows the penumbra for each applicator size, along the two main axes (along the gantry-target direction [GT] and lateral or perpendicular to the gantry-target direction [AB]). Typically, flatness below 5% and symmetry in the interval 95% to 105% are fulfilled for all applicators sizes, keeping the penumbra about 1 mm; higher dose values are obtained on the G direction vs. T and on the B direction vs. A. Since there is a small angular deviation between anode and cathode, a corresponding deviation on the electron beam appears, and therefore a slight "heel effect". Such heel effect causes an asymmetry of 1.5% of the beam profile in one direction (GT), which contributes to the deviation in the flatness of 4.3%. Without the heel effect, the flatness deviation is 2.8% on average. Values of penumbra on both axes are basically the same. Estimated uncertainties ($k = 1$) in flatness and symmetry have been approximately 1%, while for the case of the penumbra it was lower than 0.1 mm.

Depth dose evaluation

Table 3 presents the PDD data normalized at maximum (0 mm depth) up to a depth of 10 mm. The standard devi-ation of the PDD measurements was 0.25% ($k = 1$). As expected, we observed a slight increment of PDD with surface applicator diameter. At the typical prescription depth of 3 mm, the range resulted about 1%, reaching 4% at the maximum depth of 10 mm. The dose depth gradient was about 7% per millimeter. When normalized at the typical prescription depth of 3 mm, the surface dose was 23% higher.

kV stability

The kV mean value obtained by measuring using the Barracuda system and oRTIgo software with accuracy of ± 1.5% (according to the Barracuda manual) was 68.4 ± 1.0 kV ($k = 1$), which is compatible with the nominal value of 69.5 kV as specified in the Esteya unit.

HVL evaluation

The HVL evaluation results from both the oRTIgo calculation and the fit for the 10 mm surface applicator size were 1.86 ± 0.20 mm Al, and 1.82 ± 0.16 mm Al ($k = 1$), respectively. As it can be observed, the results given by oRTIgo software are in good agreement with the data obtained by the negative exponential fit.

Absolute dose evaluation

The measured absolute-rate values for all the available surface applicators at 0 mm depth are shown in Table 4. The output range within applicators was 10%. Treatment time for a typical prescription at 3 mm depth with the 30 mm diameter applicator of 6 Gy to 7 Gy per fraction gives 109 s to 127 s. Dose rate decreases with applicator size.

Table 1. Flatness and symmetry results of the Esteya unit results for all available surface applicators. Uncertainties are given with a coverage factor *k* = 1

Surface applicator diameter [mm]	Flatness		Symmetry	
	GT	AB	GT	AB
30	4.3 ± 0.3%	2.8 ± 0.1%	104.8 ± 0.5%	96.6 ± 0.3%
25	3.7 ± 0.8%	3.0 ± 2.3%	104.6 ± 0.6%	94.1 ± 2.7%
20	3.4 ± 0.6%	3.5 ± 0.5%	103.3 ± 0.8%	97.2 ± 0.8%
15	4.4 ± 0.1%	4.6 ± 1.2%	103.4 ± 0.4%	95.9 ± 3.1%
10	6.9 ± 1.0%	7.4 ± 1.6%	106.0 ± 1.4%	99.0 ± 9.5%

Table 2. Penumbra evaluation results for all available surface applicators. Uncertainties are given with a coverage factor *k* = 1

Surface applicator diameter [mm]	Direction penumbra [mm]			
	G	T	A	B
30	0.88 ± 0.02	0.98 ± 0.04	1.10 ± 0.09	1.14 ± 0.07
25	1.15 ± 0.01	1.25 ± 0.04	1.30 ± 0.01	1.31 ± 0.01
20	1.04 ± 0.06	1.10 ± 0.05	1.27 ± 0.04	1.22 ± 0.03
15	0.97 ± 0.03	1.05 ± 0.06	1.12 ± 0.15	1.12 ± 0.02
10	0.86 ± 0.01	0.87 ± 0.18	1.06 ± 0.10	0.99 ± 0.15

Table 3. PDD data for each surface applicator size normalized to the maximum value at 0 mm

Depth [mm]	Surface applicator diameter [mm]				
	10	15	20	25	30
0	100.0%	100.0%	100.0%	100.0%	100.0%
1	92.7%	92.3%	92.4%	92.4%	92.5%
2	87.6%	85.9%	86.2%	86.3%	86.5%
3	80.1%	80.6%	80.4%	81.0%	81.0%
4	73.1%	74.4%	74.6%	75.5%	75.8%
5	68.6%	69.9%	70.9%	71.3%	71.7%
6	63.8%	65.0%	65.8%	67.0%	67.4%
7	59.1%	60.7%	61.8%	62.6%	62.9%
8	55.9%	57.0%	57.9%	58.4%	59.0%
9	51.7%	52.5%	54.3%	55.1%	55.3%
10	48.5%	50.0%	51.3%	52.2%	52.7%

Spectral evaluation

The spectra of six different tubes have been measured. Their average energy is 36.2 ± 0.1 keV, (k = 1). Figure 4 shows the Esteya system measured spectrum compared with the spectra obtained with Penelope (average energy 36.2 keV) and SpekCalc (average energy 36.6 keV).

Linearity

Linearity of the Esteya EBS was checked for absorbed doses between 1 Gy and 6 Gy, which implies an interval of 80 s to 131 s, and intensity of 0.5 mA to 1.6 mA. A linear fit of the results yielded a correlation coefficient R^2 = 0.994. So, the system presents an adequate linearity along a wide dose range for which it has been designed. It agrees with manufacturer specification: "The timing of the X-ray beam is controlled by the primary timer, and is checked by an independent secondary timer, manufacturer guarantees that timing accuracy is within 1%".

Leakage estimation evaluation

In the most adverse situation, the corrected leakage value obtained was smaller than 2 μGy/s. Taking into account the dose rate measured for the used surface applicator, this leakage value would be less than 0.01% of the delivered dose. These values can be considered as an upper threshold, concluding that the system has negligible leakage.

Uncertainty analysis

D_{wQ} uncertainties have been evaluated, taken into account that the product $N_{D,W,Q_0} K_{QQ_0}$ has an uncertainty of 3.3% (k = 2) and M_Q of 0.25% (k = 1), it results in a uncertainty of 1.7% (k = 1).

Table 4. Absolute dose rate values and its standard deviation (k = 1) at 0 mm depth for the five surface applicators

Applicator diameter [mm]	Dose rate at 0 mm depth D_w (Gy min^{-1})
10	3.004 ± 0.013
15	3.122 ± 0.001
20	3.197 ± 0.002
25	3.300 ± 0.001
30	3.295 ± 0.001

— 70 kV SpekCalc
— Penelope
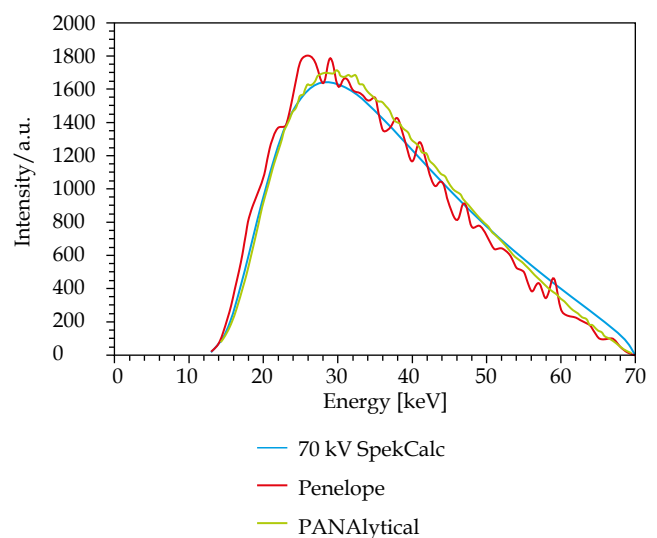— PANAlytical

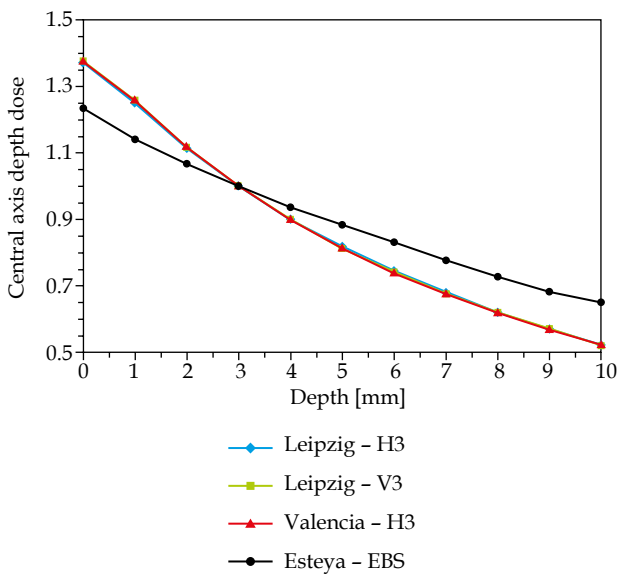**Fig. 4.** Esteya electronic brachytherapy system spectrum

Fig. 5. 30 mm applicator central axis depth dose normalized @ 3 mm
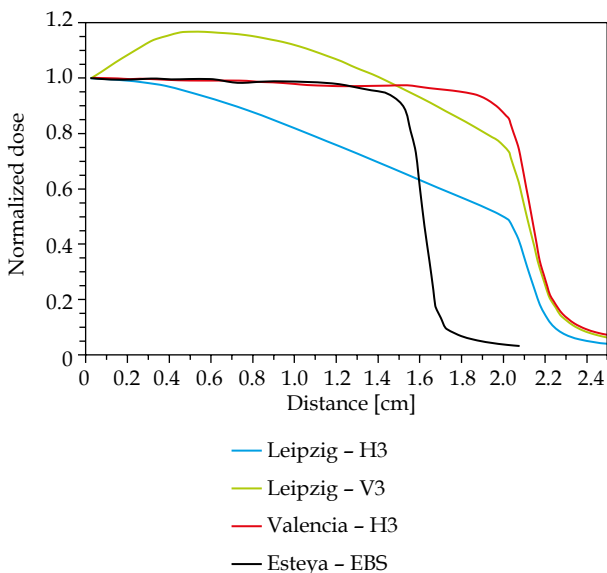

Fig. 6. Half profiles at 5 mm depth normalized to the central axis value for the 30 mm in diameter applicators

Discussion

In Figure 5 we show a comparison of the 30 mm in diameter applicator – PDD curves for the two Leipzig versions (horizontal and vertical) from Nucletron [3], the Valencia applicator [2], and the results in this work for the Esteya electronic brachytherapy system. Up to the prescription depth, the PDD is improved with a lower surface dose. As a consequence, deeper tissues receive a higher dose. In Figure 6, dose profiles for the 30 mm in diameter applicators are compared, showing the high homogeneity obtained with the Esteya system, even improving the Valencia's profile. The (80-20%) penumbra values are significantly improved from Leipzig (6.2-9.5 mm) to Valencia (1.9 mm) and Esteya (1.1 mm).

Conclusions

Commissioning and dosimetric characteristics of the Esteya system are presented. The new Esteya system of electronic brachytherapy shows excellent flatness and penumbra as in the Valencia applicator case, but with an improved PDD (allowing treatment of lesions up to 5 mm deep) and increased dose rate (reducing the treatment time). Because of the low energy of Esteya system, it allows HDR brachytherapy superficial treatment within a minimally shielded environment.

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Disclosure

Authors report no conflict of interest.

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