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A Theoretical Design of a Flattening Filter to Improve Field Uniformity of a Superficial Therapeutic X-Ray Beam

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ABSTRACT. A Monte Carlo model has been developed using the EGS4 code to aid the design of a flattening filter, to improve field uniformity of a superficial X-ray machine. The machine is operating at 90 kV and filtered with a 1.1 mm aluminium filter. In the theoretical simulation the original flat filter was replaced by a varying thickness filter to improve the uniformity across field sizes 20, 5 and 2 cm diameter as well as hardening the beam. Simulation results showed that flatness of the beam profile was improved for the 20 cm field size from ±7.3% to ±1.1% across the anode/cathode direction, and from ±7.7% to ±3.2% in the anode/cathode direction. For the 5 cm field size the improvement was from ±4.6% to ±3.1% and from ±5.5% to ±3.4%, and for the 2 cm field size from ±3.1% to ±2.4% and from ±10.2% to ±9.5%, in the same directions, respectively. Beam quality simulations were made and the original half-value layer was reduced from 2.21 ± 0.09 mm aluminium to 2.04 ± 0.09 mm aluminium. The study demonstrated that it was possible to build a filter capable of flattening the beam profile for different sized applicators without significantly changing the penetrating ability of the beam.

KEYWORDS: EGS4, Monte Carlo, Simulation, Therapeutic X-ray Beam.

Introduction

X-ray machines operating in the range of 50 to 150 kV are called superficial therapy machines. To increase the penetrating quality of the produced photon beam, aluminium filters of up to 6 mm are added. Half value layer (HVL) is used for describing the penetrating ability of the beam. It is defined as the thickness of a material penetrated by one half of the radiation and is expressed in units of distance (mm or cm). The HVLs are generally in the range of 1 to 8 mm aluminium for superficial machines. The source-surface distance (SSD) is normally in the range of 10 to 30 cm and the machine is usually operated at a tube current of 5 to 30 mA. Stainless steel cones are used to collimate the beam, and the surface to be treated is placed in contact with the end of the cone[1].

To minimize the damage to healthy tissue and to ensure that the target area is exposed to sufficient radiation, it is necessary to ensure that the dose delivered falls within acceptable tolerances[2-4]. This has a significant effect on the requirement for beam uniformity and dose uniformity within the treatment volume[5,6]. Indeed Brahme[5] suggests that to ensure tumour control it is better to have an overflattened beam rather than an underflattened one. In addition, ICRU 50[7] recommendations for dose uniformity state that this should be within +7% to –5% of prescribed dose within the treatment volume.

The uniformity of an X-ray beam directly beyond the target varies across the field and, therefore, there is a general need in radiotherapy to *flatten* the beam profile to irradiate uniformly the target area of the patient. Megavoltage accelerators contain a flattening filter to produce a uniform photon beam profile within recognized specifications[8]. Electron beams are also subject to flatness specifications. However, for the older kilovoltage equipment, used for treatment of superficial lesions, the flatness problem is more pronounced. The distribution of radiation intensity from the reflection target in an X-ray tube is neither symmetrical nor uniform, and can not be easily corrected with a flattening filter because of the limited radiation output available. The largest changes in the beam intensity are observed in the direction along a line parallel to the tube axis. The exposure rate of the X-ray beam decreases from the cathode to the anode direction of the beam. This variation is known as the heel effect[1].

Although the role of kilovoltage treatment units has been diminished by the widespread availability of high energy linear accelerators producing photon and electron beams, many of these units remain as an essential part of many departments[9-14]. To improve flatness and symmetry in kilovoltage units, a perspex flattening filter was designed[12]. The filter has improved the flatness and symmetry of a 300 kVp unit by 8% and 7% respectively, particularly for large field sizes such as those used in palliative treatments of the spinal column.

The purpose of this work was to use the Electron Gamma Shower (EGS4) Monte Carlo code[15] to design a flattening filter capable of improving field uniformity of a superficial X-ray machine. In the simulation the existing aluminium filter is replaced by a varying thickness aluminium filter to enhance the uniformity of the beam while ensuring enough material was placed in the beam to retain the beam quality. The filter was designed to be suitable for 20, 5 and 2 cm diameter applicators.

Methods

The Monte Carlo Technique

The Monte Carlo technique[16-18] is used in a wide range of scientific applications and the phrase has a variety of different meanings. In terms of radiation transport, it can be defined as the simulation of individual particles using machine-generated random numbers to sample the probability distributions that control physical processes. By simulating a large number of histories, information can be obtained about the average values of macroscopic quantities such as energy depositions. Further, since one follows individual particle histories, the technique can be used to obtain information about the statistical fluctuations of particular kinds of events. It also possible to use the Monte Carlo technique to obtain answers which cannot be addressed by experimental investigation, such as labeling single or multiple scattered photons.

For this work, the Monte Carlo technique was chosen to aid the design of a flattening filter with varying thickness. Simulations will be made using the designed filter with different treatment field sizes. Once the model proves to be effective, a real filter could be machined and tested experimentally.

The EGS4 Code System

Photon trajectories along the different components of the X-ray system were simulated using the EGS4 code[15]. The code provides an efficient way of simulating complex systems involving the transport of photons and electrons. The general structure of the EGS4 code is shown in Fig. 1. It consists of two distinct components: the PEGS4 preprocessor and the EGS4 simulation code. PEGS4 creates data sets for each element, compound or mixture used in the simulation, which are read in by the HATCH routine of the EGS4 code itself. The user is responsible for writing three routines: MAIN, HOWFAR, and AUSGAB which form what is known as the user code. MAIN performs any initialization necessary for the simulation, including the media to be used, particle parameters and cut-off energies and geometry of the simulation. Having called HATCH to obtain media data sets, MAIN then repeatedly calls SHOWER, once for each incident particle. SHOWER and its various subroutines simulate the particle and its products until they leave the region of interest, reach the end of their track or are discarded. Although these routines are never called directly by the user, they themselves frequently call two user-written subroutines: HOWFAR and AUSGAB. HOWFAR is used to determine the distance to the next medium boundary along the current path, and AUSGAB is called to score energy and any other parameters of interest. All the simulations in this work were performed using a 450 MHz Pentium II with 32 MB EDO Memory PC.

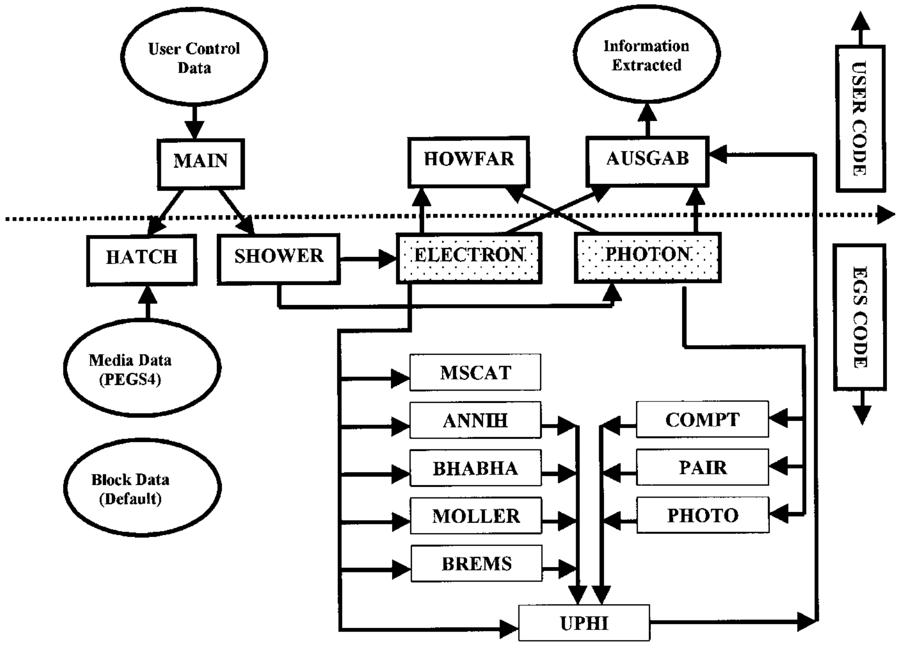

FIG. 1. The general structure of the EGS4 Monte Carlo code.

X-Ray System Modeling

The X-ray system was modeled on an existing experimental set-up, which was adapted from the Pantak (EMI) Ltd, UK, superficial X-ray tube model HC150. The maximum voltage and tube current were 150 kVp and 20 mA respectively. A schematic diagram of the system modeled is shown in Fig. 2. For all calculations, the operating voltage between the anode and the cathode was assumed to be 90 kVp. A FORTRAN program called "XSPEC.for" was used to model the X-ray tube output as a photon source for the system[19]. It calculates the X-ray tube spectra for a given kVp value, a given anode angle and tungsten as target material. In our calculations the anode angle was assumed to be 30º. The theory for the spectrum calculation in the program was taken from Birch *et al.*[20]. An output spectrum obtained from XSPEC is shown in Fig. 3. The designed filter was assumed to be made of aluminium with varying thickness (Fig. 2) and suitable for field sizes of diameter 2, 5 and 20 cm. Beam profiles were determined from the calculations along the anode to cathode axis and across that axis. Hereafter, the profiles along that axis are referred to as crossplane scans and those across the axis as inplane scans. For each simulation performed the total number of incident photons was 2×10^6 photon. Air was assumed to be the surrounding medium. SSD for the applicators of diameter 2 cm and 5 cm was 20 cm, and 30 cm for the 20 cm diameter applicator. All profiles simulated measurements were investigated at a depth of 1 cm below the surface. Point detectors tallies were used. Satisfactory statistical standard deviations were obtained for doses for all beam profiles (< ± 5%).

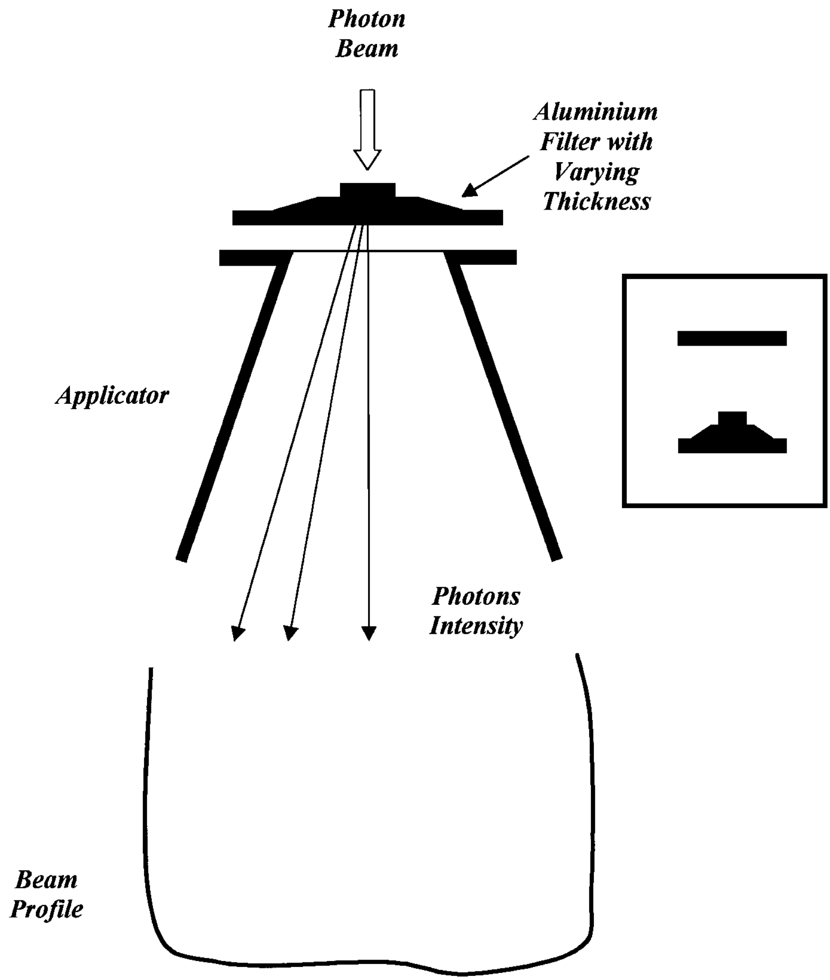

FIG. 2. Schematic representation of the simulated X-ray machine. SSD = 20 cm for 2 and 5 cm diameter applicator and 30 cm for the 20 cm diameter applicator. The right insert shows the original filter (top) and the designed varying thickness filter (bottom).

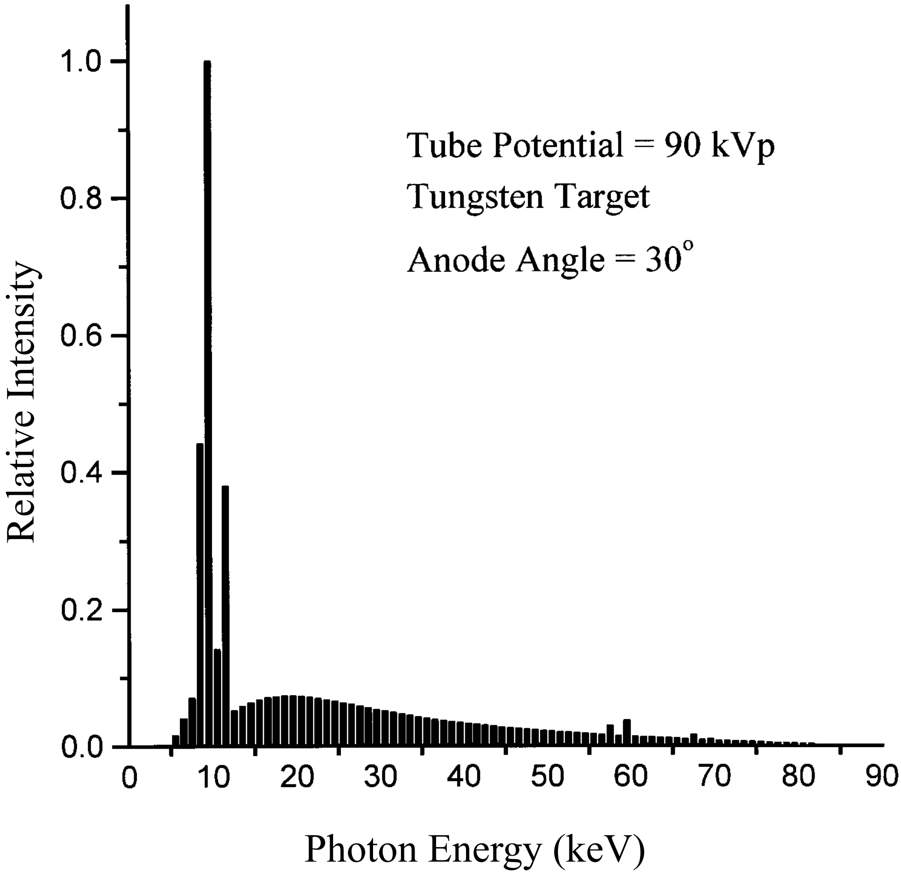

FIG. 3. X-ray spectrum calculated using XSPEC program.

HVL Measurement Simulations

Determination of HVL involves the measurement of exposure at a selected point in a beam as increasing thickness of the appropriate attenuating material are placed in the beam[1]. In this work, HVLs for both the original filter and the varying thickness filter were calculated using the EGS4 code. Narrow beam geometry situation was simulated. A 4 mm thick piece of lead with a central aperture of 1 cm diameter was placed at the end of the 2 cm diameter applicator. The detector was simulated as a point detector and therefore, point detector tally was used. The point detector was placed at a distance of 30 cm from the lead aperture. Thin sheets of aluminium were placed directly between the lead aperture and the point detector. Several EGS4 runs were performed using 2×10^6 photons for both the original filter and the varying thickness filter, and the HVL was calculated in each case.

Results

Results were expressed by means of a graphical representation of the simulated beam profiles and also by a numerical description of the beam uniformity parameters. Both methods were useful when comparing the original beam profiles with the new beam profiles obtained with the simulated filters. The graphical depiction gave a visual indication of the intensity across the field with the intensity normalized at the beam centre for each field size. However, it was desirable to characterize the changes in the profiles by a quantitative analysis.

The uniformity was assessed over 80% of the geometrical field width, referred to as "the area". A parameter called flatness (*Flattn*) was defined as

$$Flattn = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} \times (100) \tag{1}$$

where D_{min} is the minimal dose and D_{max} the maximal dose in "the area." A parameter D_{av}, the averaged dose was defined as

$$D_{av} = \frac{D_{\max} + D_{\min}}{2} \tag{2}$$

Both the quantitative results and the graphical profiles were used in assessing the profile changes as the graphs conveyed a large amount of visual information.

In Fig. 4-6 the orthogonal profiles for the inplane and cross plane directions for each field size are compared. The comparable numerical results are given in Tables 1-3. The difference between the beam quality of the original filter and the designed filter was assessed by calculations of the HVL. Calculations were made for a narrow beam detected by a suitable detector positioned approximately at 50 cm from the source. Since the designed filter was of a reduced thickness compared to the original filter a lower beam quality was expected. The calculated result of 2.04 ± 0.09 mm aluminium HVL for the final filter in contrast to 2.21 ± 0.09 mm aluminium for the original filter confirmed the theoretical considerations.

Discussion

For the 20 cm diameter applicator the shape of the new beam profile (Fig. 4) plus the change of the flatness parameters (Table 1) demonstrated an improvement of the uniformity. In the crossplane direction, the intensity fall from the right side to the left side is likely due to the heel effect and can be also observed in the original beam profile. The same effect is true for the inplane scans. For the smaller 5 cm field size the profiles in Fig. 5 also show the heel effect and some improvement in uniformity. Beam uniformity change (Table 2), although not as great as for the 20 cm diameter field, shows an overall improvement was achieved. In comparison to the original beam profile for the 2 cm applicator (Fig. 6) the visual impression is that no significant improvement can be seen although the beam edges are, as in the previous scans, sharper. Numerically, however (Table 3), the uniformity has improved slightly.

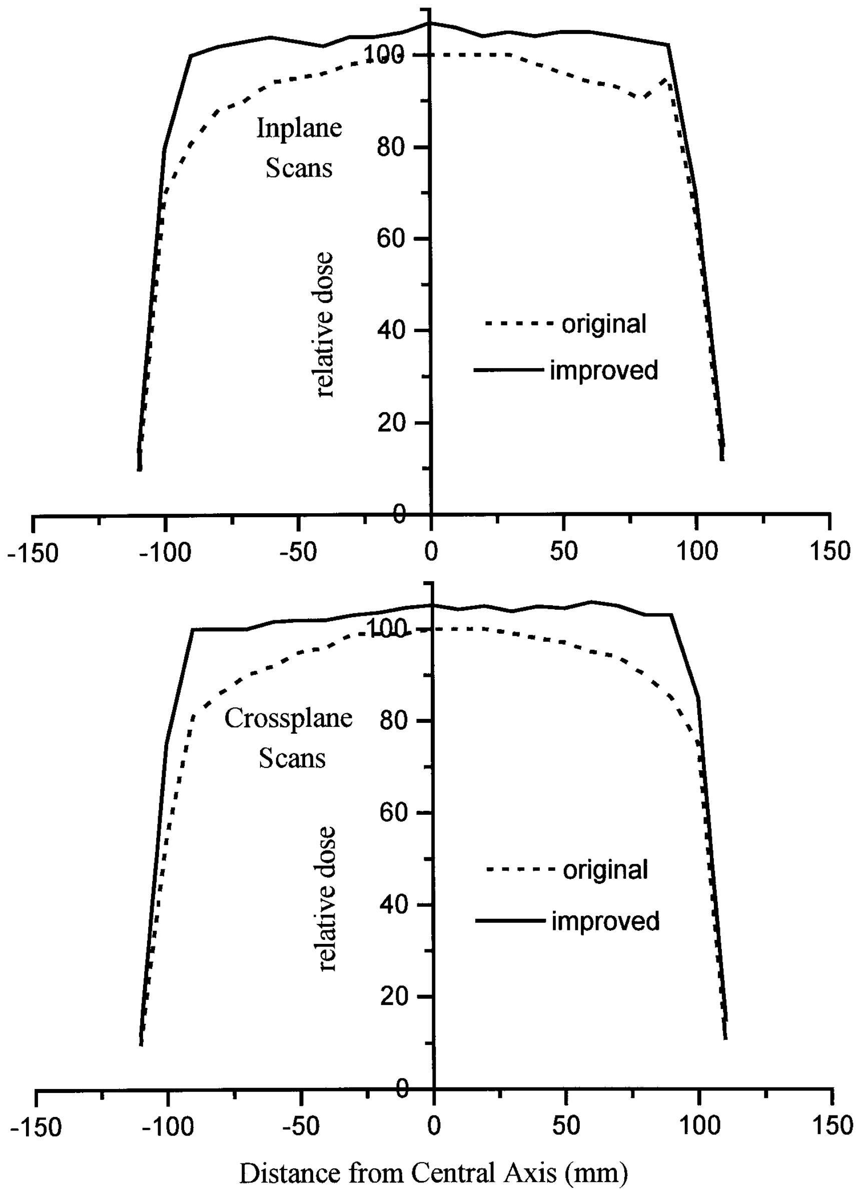

FIG. 4. Comparison of original and improved beam profile for 20 cm diameter applicator.

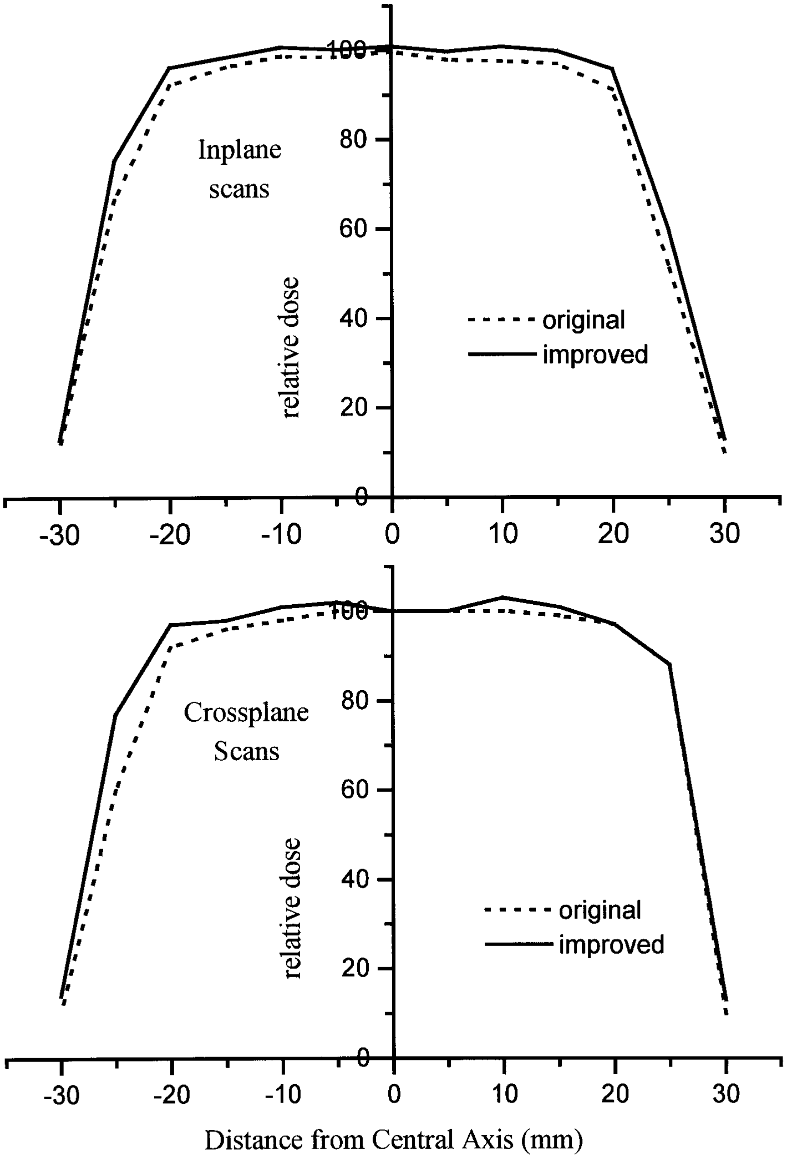

FIG. 5. Comparison of original and improved beam profile for 5 cm diameter applicator.

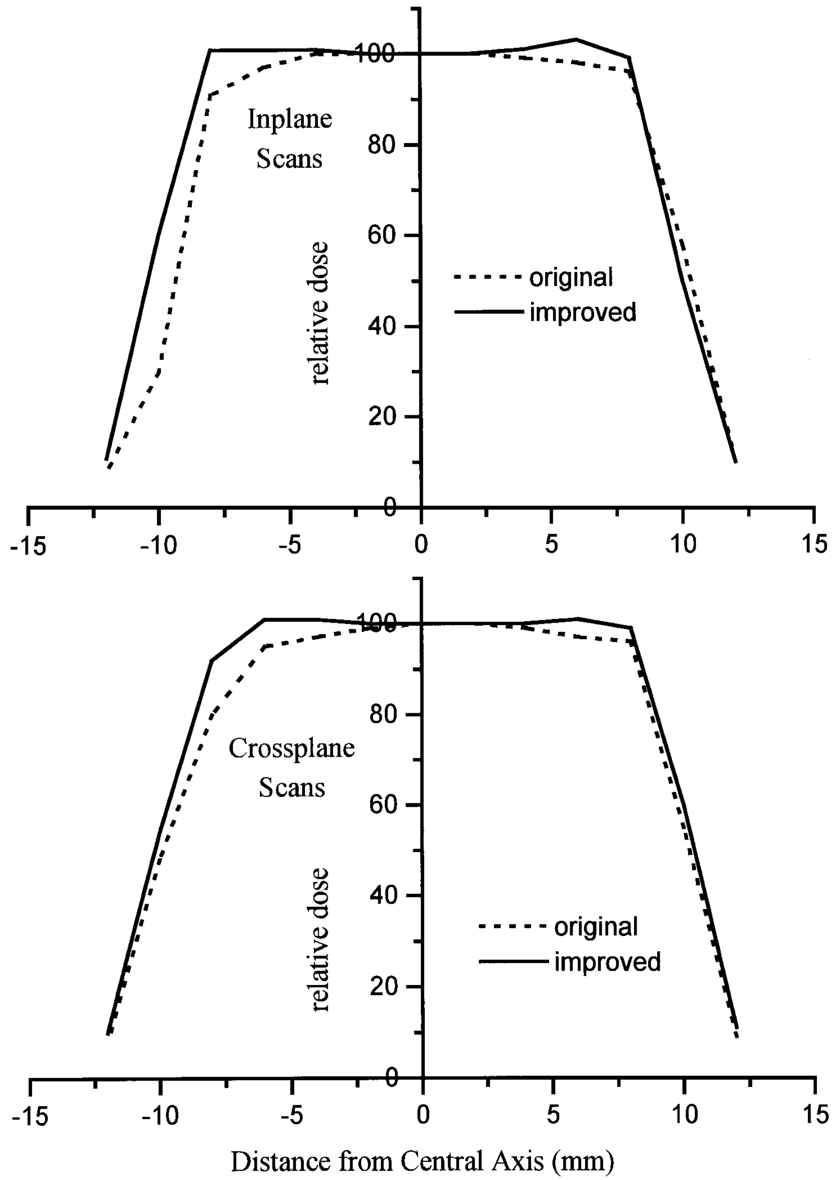

FIG. 6. Comparison of original and improved beam profile for 2 cm diameter applicator.

TABLE 1. Numerical data describing the beam profile for field size 20 cm diameter.

	D_{av}	D_{max}	D_{min}	*Flattn*
∅ 20 inplane (original)	96.0	103.0	89.0	±7.3%
∅20 inplane (improved)	100.3	101.5	99.1	±1.2%
∅ 20 crossplane (original)	92.6	99.7	85.4	±7.7%
∅ 20 crossplane (improved)	100.0	103.2	96.8	±3.2%

TABLE 2. Numerical data describing the beam profile for field size 5 cm diameter.

	D_{av}	D_{max}	D_{min}	*Flattn*
∅ 5 inplane (original)	95.8	100.2	91.4	±4.6%
∅ 5 inplane (improved)	98.1	101.1	95.0	±3.1%
∅ 5 crossplane (original)	95.8	101.0	90.5	±5.5%
∅ 5 crossplane (improved)	98.5	101.8	95.1	±3.4%

TABLE 3. Numerical data describing the beam profile for field size 2 cm diameter.

	D_{av}	D_{max}	D_{min}	*Flattn*
∅ 2 inplane (original)	96.7	99.7	93.7	± 3.1%
∅ 2 inplane (improved)	97.9	100.2	95.5	± 2.4%
∅ 2 crossplane (original)	90.9	100.1	81.6	±10.2%
∅ 2 crossplane (improved)	91.3	100.0	82.6	± 9.5%

As expected, the most significant alteration of the beam profile was achieved for the 20 cm applicator size since the original beam profile showed the least flat, while the beam profile for 2 cm applicator was influenced least of all by the new filter.

Due to the replacement of the flat 1.1 mm aluminium filter with the filter of varying thickness an alteration of the energy spectrum incident on the patient was expected. Although the calculated beam quality did not change greatly, since filter thickness is almost negligible in some parts of the filter, the HVL value of 2.04 mm aluminium may not be valid across the whole field. Further calculations should be performed with changing the thickness of the filter and by providing additional low atomic number materials in the base of the applicators. Such flattening should compensate for the effects of scatter on the skin and reduce the variation of central axis dose with field size. Experimental verification of the new filters will be a subject of further research.

Conclusion

The aim of this work was to design a flattening filter to improve field uniformity of a superficial X-ray machine. The results presented indicate that it is possible to have such a filter for a treatment field size of 20 cm. The improvements in the flatness of the beam were ±1.2% and ±3.2% for inplane and crossplane respectively. However, for the 5 cm and 2 cm fields the improvements were less effective.

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تصميم نظري لمرشــح اســتوائي لتحســين التمــاثــل الحقلي لجهــاز أشــعة ســينية علاجيــة سطحيــة

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المستخلص . تم في هذا البحث تطوير نموذج نظري (مونت كارلو) باستخدام برنامج الـ EGS4 ، وذلك لتصميم مرشح استوائي لتحسين التماثل الحقلي لجهاز أشعة سينية يستخدم في علاج الأورام السطحية . يعمل هذا الجهاز تحت فرق جهد ٩٠ كيلوفولت ١٠ ملي أمبير ، ويستخدم مرشح من الألمنيوم ذو سمك ١ , ١ مم . عند القيام بالمحاكاة النظرية . تم استبدال المرشح الأصلي للجهاز بمرشح آخر ذى سمك متغير . وذلك لتحسين استوائية حقول التشعيع ذات الاقطار ٢ , ٥ , ٢٠ سم بالإضافة إلى تقوية الأشعة الناتجة . أظهرت نتائج الدراسة أن استوائية الأشعة قد تحسنت بالنسبة لحقل التشعيع ٢٠ سم من ± ٣ , ٧٪ إلى ± ١ , ١٪ وذلك عبر اتجاه المصعد / المهبط ، ومن ± ٧ , ٧٪ إلى ±٢ , ٣٪ في اتجاه المصعد / المهبط . وبالنسبة لحقل التشعيع ٥ سم فقد كان التحسن من ± ٦ , ٤٪ إلى ± ١ , ٣٪ ومن ± ٥ , ٥٪ إلى ± ٤ , ٣٪ في نفس الاتجاهين السابقين على التوالي . وبالنسبة لحقل التشعيع ٢ سم فقد كان التحسن من ± ١ , ٣٪ إلى ± ٤ , ٢٪ ومن ± ٢ , ١٠٪ إلى ± ٥ , ٩٪ في نفس الاتجاهين السابقين على التوالي . أما بالنسبة لقوة الأشعة المتولدة ، فقد كان التغير طفيفًا في سمك النصف حيث كان التغير من ± ٢١ , ٢ ±٠٩ , ٠مم إلى٠٤ , ٢ ±٠٩ , ٠ مم ، بالتالي أثبتت هذه الدراسة أنه من الممكن تصميم مرشح استوائي للأشعة السينية لعدة حقول تشعيع مختلفة مع المحافظة في نفس الوقت على القوة الاختراقية للأشعة .

كلمات مفتاحية : محاكاة نظرية ، الأشعة السينية العلاجية ، برنامج الـ EGS4 ، مرشح استوائي ، حقول التشعيع .