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Original Article

Evaluating the Effects of Field Size on Beam Homogeneity Coefficient in the Superficial Radiotherapy Machine Using Empirical Method and Simulation

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Abstract

Introduction
Superficial X-ray therapy is one of the most important treatment methods in radiotherapy especially in the treatment of superficial skin lesions (Up to 300 kVp). Quality of the X-ray beam that can be expressed by Half-Value Layer (HVL), are important indices for this type of treatment effective energy of photon and Homogeneity Coefficient (HC).
Materials and Methods
The HC of the superficial X-ray machine at 180 kVp was determined by an experimental method and also by simulation (EGSnrc code) and the results were compared. The exposure after the first (0.5 mmCu) and second (1 mmCu) attenuation layers were measured by Farmer dosimeter for three different field sizes. The HC was derived from these experimental data and was compared with corresponding results acquired by EGSnrc code package. The BEAMnrc code was used to transport photons and electrons at exit level of the applicator, DOSXYZnrc code for calculation of absorbed dose in the phantom, and BEAMDP for drawing the output spectra.
Results
Results showed that the mean percentage difference of errors obtained by experimental data and simulation method is 3.3% and the average energy of output spectra in 180 kVp after passing through filters and attenuation layers increases to 15.3% to 25.4%.
Conclusion
The maximum percentage difference of errors for the applied methods is higher than analogous devolves elsewhere reports which could be due to setup parameters such as SSD and field size. However, the present method has the advantage of ease of setup and matching with clinical conditions.

Keywords: EGSnrc, Homogeneity Coefficient, Ortho-Voltage Machine, Radiotherapy

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1. Introduction

Up to the 1950, most of the external radiotherapies treatments were carried out by X-rays generated at voltages up to 300 kVp. Subsequent development of higher energy machines and the increasing popularity of the cobalt-60 units in the 1950s and the 1960s resulted in a gradual demise of the conventional kilovoltage machines. However, these machines have not completely disappeared. Even in the present era of the megavoltage beams, there are some uses for the lower energy beams, especially in the treatment of superficial lesions [1, 2].

In the case of low-energy X-ray beam (below megavoltage ranges), it is customary to describe quality in terms of HVL together with effective energy, although Half-Value Layer (HVL) alone is adequate for most clinical applications. HVL is the thickness of an absorber of specified composition required to attenuate the intensity of the beam to half of its original value.

Because X-ray beams used in superficial radiotherapy are always heterogeneous in energy, it is sometimes common to express the quality of an X-ray beam in terms of the effective energy. The effective energy of an X-ray beam is the energy of photons in a monoenergetic beam which is attenuated at the same rate as the radiation in question [1, 2].

The Homogeneity Coefficient (HC) is another index of X-ray beam used in superficial radiotherapy that is a better way to reveal the quality of the X-ray beam by taking into account both the HVL and the effective energy of the beam, which is defined as the ratio [3]:

$$H = \frac{E2}{E1} \qquad (1)$$

Where, E2 is the output exposure after inserting the second attenuator layer (1 mmCu totally) and E1 is the output exposure obtained with the first attenuator layer (0.5 mmCu).

The applied MC codes in this study were the EGSnrc-based BEAMnrc and BEAMDP from the NRCC group [4-6]. The EGSnrc was developed from the EGS4 code by Nelson et al [7]. For this purpose, the latest version of the EGSnrc code was used which includes directional bremstrahlung splitting (DBS) to increase the efficiency of energy transition from the electron current to X-ray photons. The electron impact ionization model is also implemented which significantly improves the shape of the X-ray spectra [8, 9]. The treatment head was simulated in the BEAMnrc code and all data were received from the vendor for making this feasible [10, 11].

In the previous studies, the HVL index was evaluated using different experimental methods and also simulation codes (e.g., PENELOPE). Mainegra et al. proposed two methods for calculating the HVL that were in good agreement with the experimental results (i.e., 2.3% differences at most) [8]. In another study by Chica et al., the HVL was calculated by the PENELOPE code, which showed about 2% difference with the experiment [3].

Another method for evaluation of the X-ray beam quality was proposed by Chica et al. in which the ratio of absorbed dose in Z1/2 and Z1/4 depths (the depths in water in which the dose is 50 and 25% of the dose at Z0) was measured and compared with those obtained by simulation (PENELOPE). From the simulated and measured depth dose curves, they evaluated the corresponding Z1/2 and Z1/4. As for the quality indexes, no statistical differences between experimental and simulated results were observed and both the Z1/2 and the Z1/4 obtained from the experimental curves were in reasonable good agreement with the simulated ones. The corresponding quality indexes (first and second HVL and HC) were also calculated. The comparison between simulated and experimental results showed a very good agreement (at most 3%) [3].

Determination of the homogeneity index in a 180 kVp ortho-voltage machine is the first purposed of this study and in the next step we intend to evaluate the effects of the field size on this index using both experiment and simulation.

2. Materials and Methods

2.1. Measurement Method

In order to calculate the HC for the X-ray beam in the ortho-voltage machine (Stubilipan, Siemens, Germany), exposure rates (air Kerma) at SSD=50 cm on different field sizes (10×15, 8×10, and 6×8 cm^2) were measured. Exposure parameters were as follow: 120-300 kVp, 12-20 mA, Anode angle 30°, focal spot 8×8 mm^2, and HVL=0.5 mmCu with the 0.2 mmCu added filtration.

Farmer dosimeter (Nuclear Enterprise, US) was used to measure the exposure rate, comprised of the thimble chamber and the electrometer. The dosimeter was calibrated according to the Secondary Standards Dosimetry Laboratories (SSDL) of the Iranian Atomic Energy Organization (IAEO).

Measurements were performed in three stages at the distance of 50 cm from the focal spot. In the first stage, measurement was conducted without inserting the added filters, in the second stage with applying the first added filter (0.5 mmCu), and in the last stage with the two added filters (0.5+0.5=1 mmCu). The exposures were converted to cGy/min according to the TRS398 report [12].

2.2. Monte Carlo Simulation

In order to model the ortho-voltage machine, EGSnrcMP simulation code was used [8, 10, 11, 13]. The EGSnrc-base+d MC user code, BEAMnrc, was used to simulate the geometry of the head of the machine and outputs phase-space data (phase space files), which include all the particle information (i.e., the charge, position, direction, energy, and history tag for each particle). Another general-purpose MC EGSnrc user code, DOSXYZnrc, which considers the phantom divided into a large number of small volume elements, or voxels, was employed to obtain the dose distributions in the phantom [10, 11].

The components of the head of the machine including source of the X-ray (X-ray tube), output window, inherent filter (2.4 mmAl), collimator, added filter (0.2 mmCu), and applicator are depicted in Figure 1. Types of the applied materials were chosen according to PEGS4 data of EGSnrc code and 521ICRU file [14].

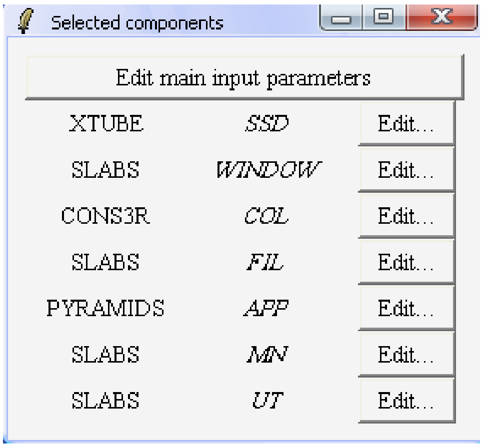


Figure 1. Component modules in the head of the machine used in the simulation.

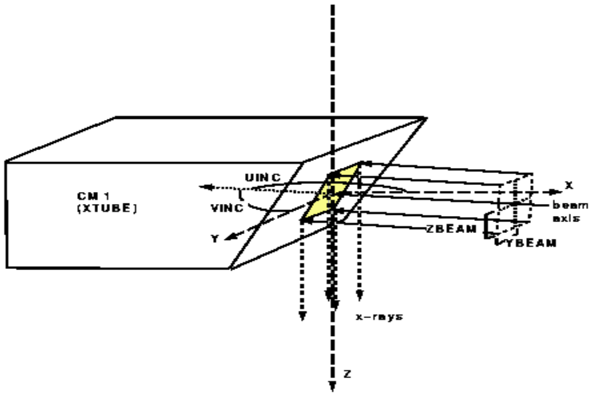


Figure 2. X-ray source used in simulation (rectangular type source with focal spot size of 8×8 mm^2).

For simulating the source of the machine, the "parallel rectangular beam incident from side" with the following specs was selected (Figure 2): target material Tungsten, anode angle 30°, focal spot size of 8×8 mm^2, Electron Energy Cut-Off (ECUT) 521 keV, (Photons Energy Cut-Off (PCUT) 1 keV, and "range rejection" 1 MeV [4].

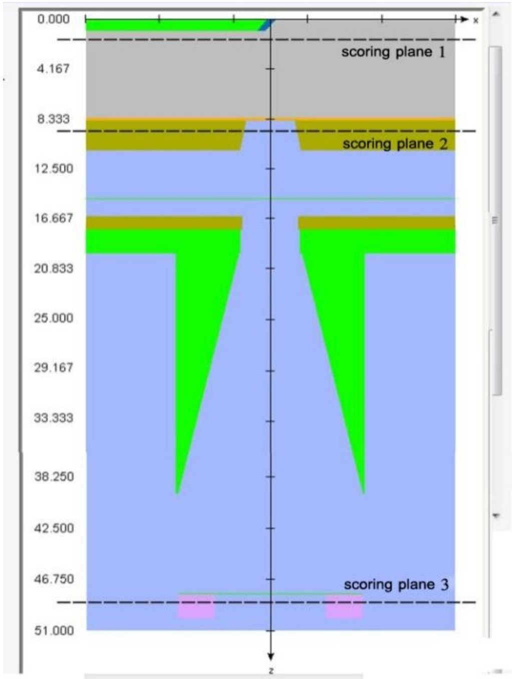


Figure 3. Geometry used for the simulation. The scoring planes (1, 2, and 3) are also depicted.

Three scoring planes in different locations were selected (Figure 3). The first scoring plane was located after the source for deriving the X-ray spectra without considering the inherent filtration, the second at the exit level of the inherent filter, and the third was located after the attenuator layer (added filter) for deriving the phase space file which was applied for calculation of air Kerma using DOSXYZnrc code [10, 11, 13].

For calculation of the HC using DOSXYZnrc code, at first, the air Kerma was calculated [15]. For this task, the "full phase space" source type was selected to irradiate the designed voxel-based phantom (i.e., voxel size 0.3×0.3×0.3 cm^3). The dose distributions calculated by DOSXYZnrc can be found in the output files, ".egslst" and ".3ddose". The file ".egslst" contains not only the dose (when asked for) and statistical data, but also the information about simulation geometry, number of histories run, CPU time used, etc. The dose output file, ".3ddose", contains the information about the 3D simulation geometry and the calculation results in a format that can be read for generating plots. In the simulation process, in each run, the variance reduction technique, DBS [16], was also applied. This increases the efficiency of energy transition from the electron current to X-ray photons. The electron impact ionization model is also implemented which significantly improves the shape of the X-ray spectra as described by Kawrakow [17].

By inserting the attenuator as a new component in the modeling, absorbed doses (air Kerma) for different field sizes (6×8, 8×10, and 10×15 cm^2) were calculated.

The BEAMnrc and DOSXYZnrc codes ran under the Fedora 7 Linux OS with a Pentium® 4 computer with the following specs: 2×3 GHz CPU and 1 Gbyte RAM. The numbers of histories in each run in the BEAMnrc and DOSXYZnrc codes were 1.5×108 and 15×108 and the total CPU times 12.5 and 6 h, respectively.

The EGSnrc-based MC user code BEAMDP was used to derive the X-ray spectra [18, 19]. For calculating the mean energy of the spectra, the formula (2) was used [8]:

$$E_{ave} = \frac{\sum_{i=1}^{n} E_i \emptyset_i \, \Delta E_i}{\sum_{i=1}^{n} E_i \Delta E_i} \qquad (2)$$

Where, Ei is the bin energy, **Φ**i bin flounce, and ΔEi bin difference between two consecutive energy bins.

3. Results

Table 1 shows the results for both experiment and simulation. Measured and calculated HC obtained by experiments and simulations were an average 0.703±0.002 and 0.727±0.08, respectively. The results also showed that the field size affected the HC between 2.72% and 6.46% in experiment and 3.6% and 8.53% in simulation (i.e., increases with the field size). It seems increasing the scattered radiation with field size causes it.

Moreover, the results revealed that the percentage difference of HC between simulation and experiment increases with the filed size.

Table 1.The homogeneity coefficient obtained by experimental and simulation methods (DOSXYZnrc code) for different field size.

Field Size (cm^2)	Homogeneity Coefficient (Experiment)	Homogeneity Coefficient (MC Simulation)	Percentage Difference
6×8	0.680±0.004	0.697±0.09	2.44%
8×10	0.699±0.002	0.723±0.08	3.32%
10×15	0.727±0.002	0.762±0.09	4.6%
Average homogeneity coefficient	0.703±0.002	0.727±0.08	3.3%

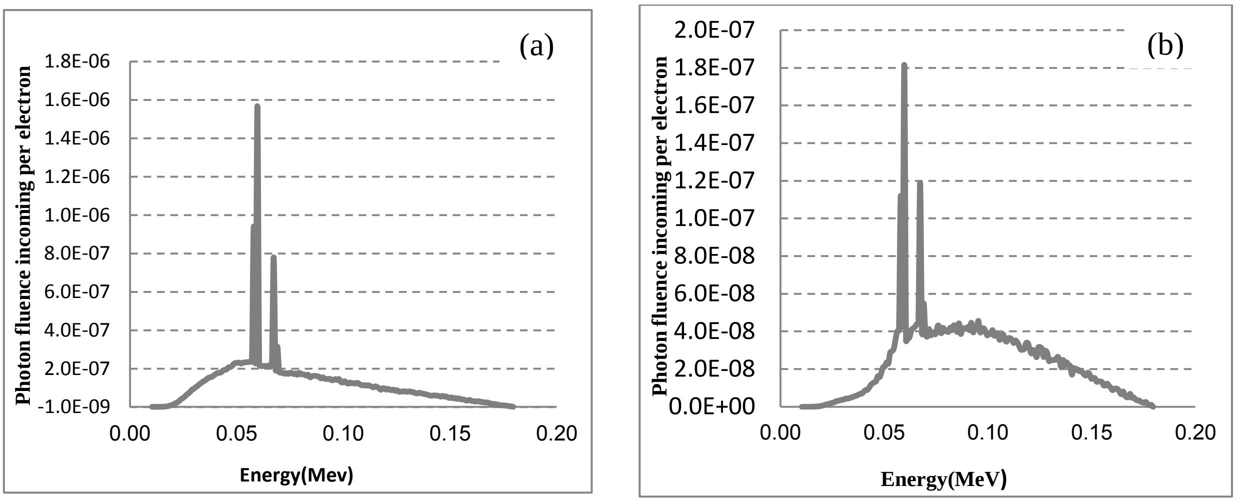
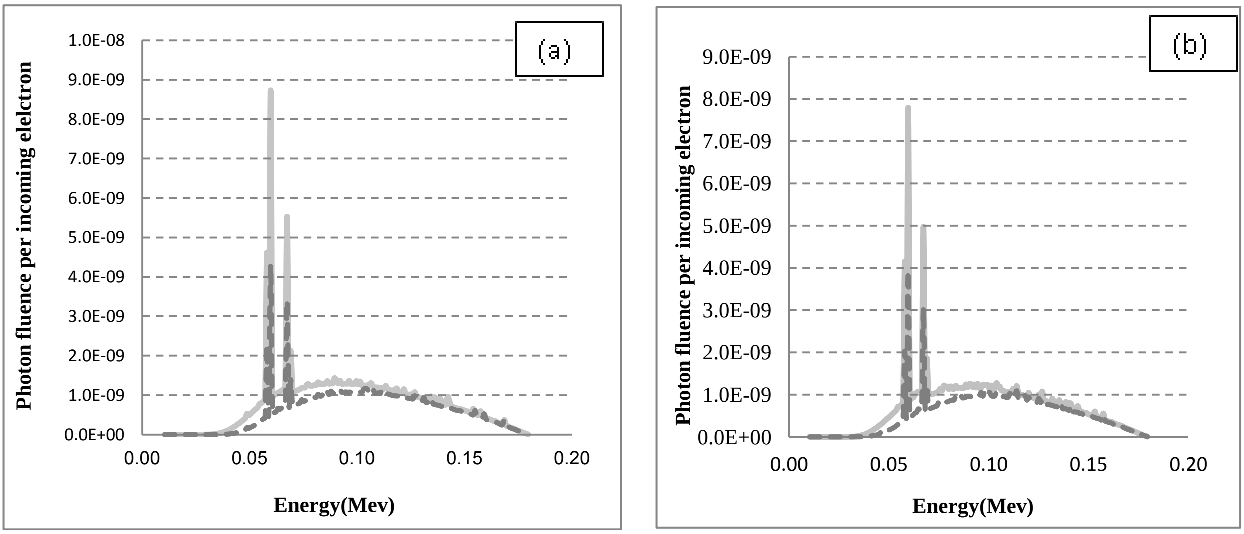


Figure 4. Output spectra of ortho-voltage machine at the 180 kVp after the X-ray source (a) and inherent filter (2.4 mmAl) (b) with relative percentage error 5.07% and 6.57%, respectively.



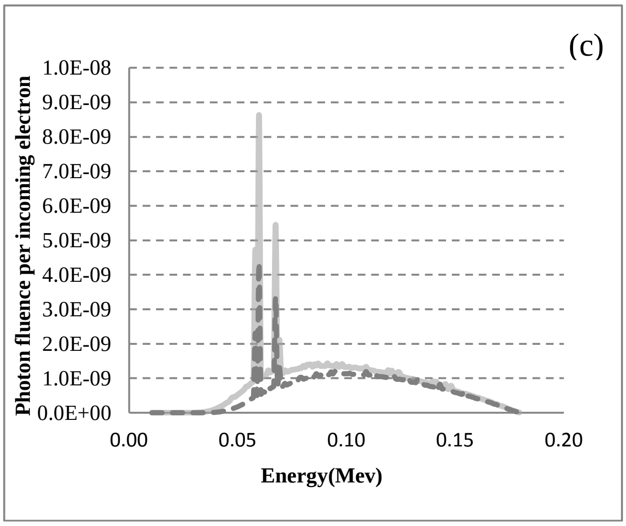


Figure 5. Output spectra of the ortho-voltage machine at the 180 kVp after the first (0.5 mmCu, —) and second (1 mmCu, ----) attenuator layers in the 6×8 cm^2 (a), 8×10 cm^2 (b), and 10×15 cm^2 (c) field sizes. The corresponding relative percentage errors were 3.83%, 3.48%, and 2.8%, respectively.

Figure 4 shows the output spectra at 180 kVp at different locations along the path of the X-ray beam, after the source (a) and after the inherent filter (2.4 mmAl) (b) with relative percentage errors of simulations being 5.07% and 6.57%, respectively.
Figure 5 shows the X-ray spectra after inserting the attenuators in different field sizes. These figures apparently show the decrease in the number of photons with increase in the thickness of attenuator layer.

These spectra were drawn using the MC user code BEAMDP at the locations where the phase space files have been obtained using BEAMnrc code.
Table 2 shows the mean energy and relative percentage error of the output spectra in the mentioned scoring planes in different field sizes. Because of beam hardening, the mean energy of the spectra increases as the X-ray beam passes through the filters and attenuator.

Table 2. Average energy of output spectra (Eave) in the ortho-voltage machine at the 180 kVp.

Average Energy of Spectrum (E_{ave}) Kev				
Position of the Scoring Plane	Field Size 6×8 (cm^2)	Field Size 8×10 (cm^2)	Field Size 10×15 (cm^2)	% Mean Relative Error
After X-ray Source	79.4	79.4	79.4	5.85%
After inherent Filter	93.8	93.8	93.8	6.59%
After First Attenuator Layer (0.5 mmCU)	97.6	97.8	98.3	5.70%
After Second Attenuator Layer (1mmCU)	104	104	104	5.50%

4. Discussion

Since some parameters in radiotherapy such as Back Scatter Factor (BSF) and percentage depth dose have indirect relation with homogeneity of the beam [19], measurement of HC has special significance in superficial radiotherapy.
In the current study, the HC of X-ray beam in an ortho-voltage machine was determined and effects of different field sizes on this were evaluated. Using the Equation (1), the HC of

the beam was obtained in three stages (i.e., without attenuator, with 0.5 mmCu, and 1 mmCu attenuator in the path of the beam) with the mean absolute error of ±0.002. The geometry in the experiment was precisely rebuilt in the applied simulation code (i.e., mean absolute error of ±0.08) and the results were compared with those obtained with the experiment.

The BEAMnrc was used to simulate the geometry of the head of the machine and outputs phase-space data and the DOSXYZnrc [10, 11], which considers the phantom divided into a large number of small volume elements, or voxels and was employed to obtain the dose distributions in the phantom.

These spectra were drawn using the MC user code BEAMDP at the locations where the phase space files have been obtained using BEAMnrc code [18, 20]. The spectra depict the photon flounce incoming per electron with respect to energy. Reduction in the number of low energy photons because of inherent filtration is visible in the Figure 4(a) similar to results obtained by Taleei et al. [21].

The mean percentage difference of the results between the experiment and simulation was 3.3% (2.44% to 4.60%) which is in fairly good agreement with those obtained in the study of Chica et al. [3], however, there are some differences in both the experiment setup and applied code of simulation.

Evaluating the effects of the field size on the HC was the novelty of this work. Results showed that the HC increased with the field size. In the experiment and simulation, the HC increased up to 6.46% (from 2.72%) and 8.53% (from 3.6%). It seems that the main reason for increasing the HC was the increase in the scattered radiation with the field size.

Simulation using DOSXYZnrc code also showed an increase in the voxel dose with the field size. Despite this fact, because of the similar thickness of the attenuator, the spectra had the same shape (Figure 5).

By considering the spectra (Figures 4 and 5) and the mean energy (Table 2) at different levels of the beam pathway, it could be concluded that the beam becomes harder when it passes through the attenuators (the hardening of the beam reached 15.3% after the first filter and 25.4% after inserting the second attenuator layer).

Ubrich et al. [22] used the BEAMDP for determination of the HVL by deriving the air Kerma. Application of the DOSXYZnrc for calculation of the output exposure and determination of the HC by modeling an air filled voxel-based phantom are other novel points of this study.

5. Conclusion

The results of this study showed the capability of EGSnrc simulation code in extracting the quality indices of superficial X-ray radiotherapy machines. This study showed that this code and the mentioned semi-empirical method can be employed as a routine clinical test tools for every radiotherapy department, especially in those with limited lab instruments.

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