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HVL evaluation of orthovoltage X-ray machine using EGSnrc code of simulation

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► ***Original article***

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ABSTRACT

Background: Making use of the orthovoltage machines in Radiotherapy, is one of the routine methods for the treatment of the superficial lesions. In this study, an important determinant of X-ray quality, the HVL (Half Value Layer), has been evaluated. ***Materials and Methods***: The HVLs of a orthovoltage X-ray machine in 120 and 180 kVp are measured, using an empirical method, in which the HVLs are derived from the absorption curves. The measured HVLs are compared with calculated (Monte Carlo simulation) HVLs. Using the BEAMDP code of simulation, the output spectra are obtained and employed for the measurement of the HVLs. ***Results***: Comparing the calculated and measured HVL values, the results show that the highest and lowest differences between the two are 4.96% and 2.27%, respectively, which are, in fairly good agreement with those obtained in the former studies. ***Conclusion***: This study shows that the EGSnrc simulation code is capable of being used for the extraction of the quality indices for the superficial X-ray radiotherapy machines. It seems that, the mentioned code, with the mentioned experimental method, can be employed as a routine clinical test tool for every superficial radiotherapy department.

Keywords: *HVL, EGSnrc, MC simulation, orthovoltage machine.*

INTRODUCTION

Up to about 1950, most of the external radiotherapy was carried out with 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 been completely disappeared. Even in the present era of the megavoltage beams, there is some use of the lower energy beams, especially in the treatment of superficial lesions (1).

Because X-ray beams used in superficial radiotherapy are always heterogeneous in energy, it is conventional sometimes 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. In the case of low-energy X-ray beams (below megavoltage ranges), it is customary to describe quality in terms of HVL together with effective energy, although HVL (half-value layer) alone is adequate for most clinical application. HVL is the thickness of an absorber of specified composition required to attenuate the intensity of the beam to half of its original value (1, 2).

The availability of advanced Monte Carlo (MC) simulation systems and the ever increasing computing power has made Monte Carlo simulations of X-rays pectra an attractive addition and alternative to experimental measurements. As a consequence, the study and characterization of X-ray tubes and radiotherapy machines using Monte Carlo simulations has become common practice (3-7).

The applied MC codes in this study were the EGSnrc based BEAMnrc and BEAMDP from the NRCC group (8-10). The EGSnrc was developed from the EGS4 code by Nelson *et al.* (11). For this purpose the latest version of the EGSnrc code is 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 (4, 12). The treatment head was simulated in the BEAMnrc code (9).

Determining and deriving the HVL and the output spectrum, in an orthovoltage machine at different kVps, using an empirical method and simulation (i.e., EGSnrc codes), is the purpose of this study. As the quality of orthovoltage beam is very important index in treating the superficial lesions and the quality is determined by HVL in these machines, deriving of this parameter could be very useful with practical aspects.

MATERIALS AND METHODS

Measurement method

For deriving the HVL of X-ray beam in the orthovoltage machine (Stubilipan, Siemens, Germany), exposure rates (air KERMAs) were measured for 120 and 180kVp voltages at SSD=100. The experimental setup is schematically depicted in the figure 1. Machine specs were as follows: Energy range 120-300 kVp, tube current 12-20 mA, anode angle 30^{o}, focal spot $8\times8mm^2$, cone size $6\times8cm^2$, and inherent filtration 2.4mmAl. Employed added filters for experiment were 0.2mmCu, 0.5mmCu and 1mm-Cu. Tube current in these experiments was 18mA.

Farmer dosimeter (Nuclear Enterprice, US) is used for measuring the exposure rate, which is comprised of a thimble chamber and an electrometer. The dosimeter has been calibrated at SSDL (Secondary Standards Dosimetry Laboratories) of the IAEO (Iranian Atomic Energy Organization) to give air KERMA by considering correct quality factor.

The attenuation curves were drawn and the fitted equations were solved for deriving the HVLs (i.e., the point at which the exposure reaches to half of its original value) for 120 and 180kVp.

Monte Carlo simulation

To model the orthovoltage machine, EGSnrcMP simulation code was used (13). The EGSnrc based MC user code BEAMnrc (9) was used to simulate the geometry of the head of the machine (i.e., including, source of the X-ray (X-ray tube), output window, inherent filter (2.4mm Al), collimator, added filter and applicator and outputs phase-space data (phase space files), which include all the particle information (i.e., the charge, position, direction, energy, and

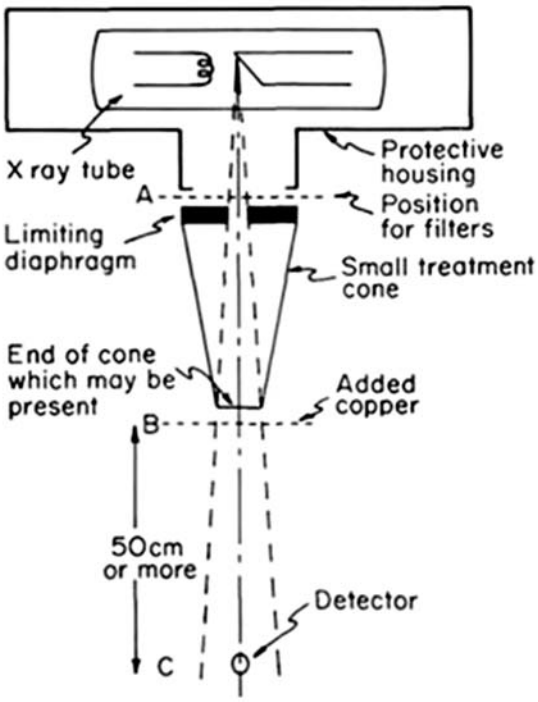

Figure 1. Schematic geometry used for experiment (1).

history tag for each particle).

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 8×8mm^2, cone size 6×8cm^2, ECUT (electron energy cut off) 521 keV, PCUT (photons energy cut off) 1 keV.

The settings in EGSnrc were: Boundary crossing algorithm – EXACT, with skin depth 3 mean free path, electron steeping using PRESTA II, spin effects ON, simple bremsstrahlung angular sampling, and cross section for bremsstrahlung production according to NIST (National Institute of Standards and Technology). Bound Compton scattering, electron impact ionization and atomic relaxations were set to ON while photoelectron angular sampling was OFF. Geometry of simulation is depicted in figure 3.

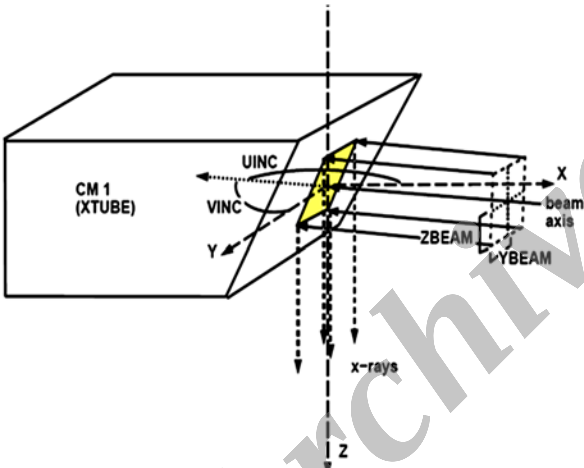

Figure 2. X-ray source used in simulation (Rectangular type source with focal spot size of 8×8mm^2).

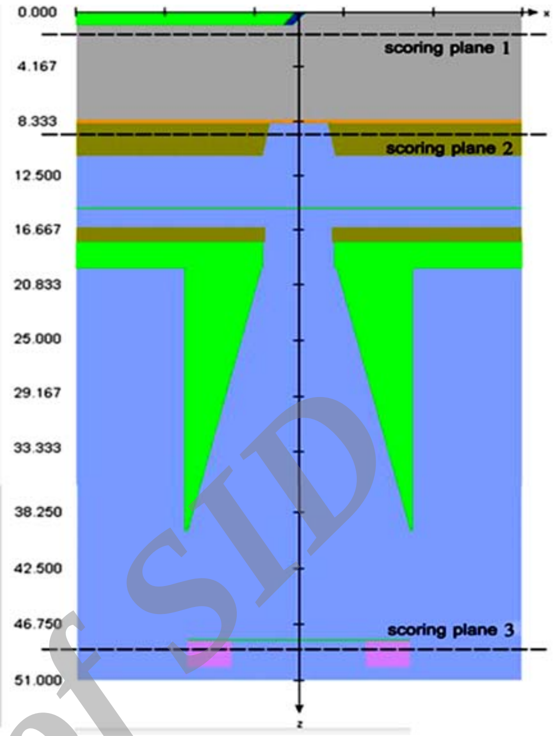

Figure 3. Geometry used for simulation. The scoring planes (1, 2, and3) are also depicted.

Determination of HVL using BEAMDP code

For the determination of the HVL, phase space data at third scoring plane (i.e., output files of BEAMnrc code) were employed as input in the BEAMDP code. Then, the HVL was calculated, using the equation 1 that output file of the BEAMDP code had the required data for deriving the HVL (14).

The summation was performed over N energy bins with width ΔE_i and midpoint energy E_i. The photon fluence per energy bin ϕ_i was extracted from the phase spaces with the utility program BEAMDP. The energy-dependent attenuation μ and mass absorption coefficients μ_{en}/ρ are from Hubbell and Seltzer (15). This summation was performed iterative until a solution was found giving the thickness of the absorber to half the K in air.

In the simulation process, in each run, the variance reduction technique, DBS (directional bremsstrahlung splitting) (4), 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 (16).

The BEAMnrc code ran under the Fedora 7 Linux OS with a Pentium® 4 computer with 2×3 GHz CPU and 1Gbyte RAM. The numbers of histories in each run was 1.5×10^8 with the total CPU time 12.5h.

$$\frac{K(t)}{K(0)} = \left(\sum_{i=1}^{N}\varphi_i E_i\left\{\frac{\mu_{en}}{\rho}(E_i)\right\}_{Air} . exp[-\mu(E_i)_{Absorber}t]\Delta E_i\right).\left(\sum_{i=1}^{N}\varphi_i\, E_i\left\{\frac{\mu_{en}}{\rho}(E_i)\right\}_{Air}\Delta E_i\right)^{-1} = 0.5 \qquad (1)$$

The EGSnrc based MC user code BEAMDP was used to derive the X-ray spectra at different energies (15, 17). For calculating the mean energy of the spectra the following equation was used (18):

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

Where, E_i is the bin energy, Φ_i bin flounce, ΔE_i bin difference between two consecutive energy bins.

RESULTS

Figure 4 (a and b) shows the absorption curves for 120 and 180 kVp beam energies. In these figures the mean exposure rates (nC/min) were drawn against the thickness of attenuator layers. The average absolute error of measurement for 120 and 180 kVp beam energies were ±0.032 and ±0.017, respectively (n=3).

Table 1 shows the results of measurement and simulation in deriving the HVL for different beam energies. The effective energy (E_{eff}) and average energy (E_{ave}) of the beam are also shown in the table. Percentage difference between simulation and measurement were at most 4.96%.

The figure 5 (a and b) show the output spectra for 180 and 120 kVp beam energies. These beam spectra were drawn at specified scoring planes using the BEAMDP code. The phase space data at these scoring planes were obtained using the BEAMnrc code.

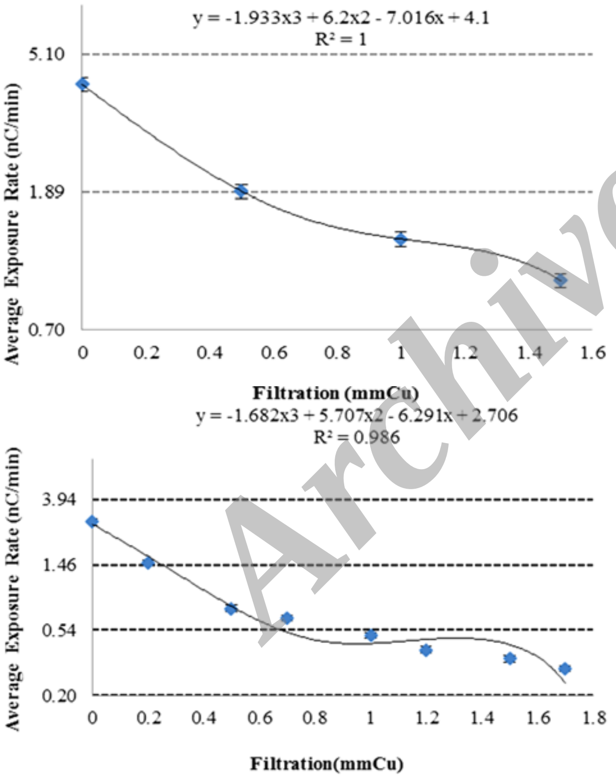

Figure 4. Semi-log attenuation curves obtained using empirical method for 120 (a) and 180kVp (b) energies.

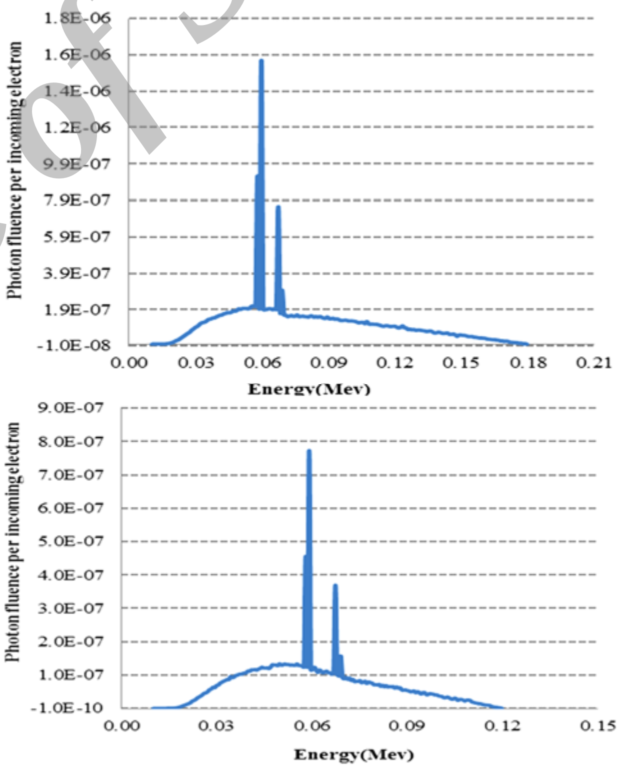

Figure 5. Output spectra for orthovoltage X-ray in 180 (a) and 120kVp (b) energies. Average percentage relative errors of simulations were 4.91 and 5.45% respectively.

Table 1. HVL of X-ray beam in 120 and 180kVp obtained using experiment and simulation. Percentage difference between two methods, E_{eff} and E_{ave} are also shown.

Energy (kVp)	HVL(mmCu) (Experiment)	HVL(mmCu) (MC)	Difference (%)	E_{eff} (keV)	E_{ave} (keV)
120	0.264±0.046	0.272±6.86%	2.94%	49.9	60.9
180	0.479±0.017	0.504±5.45%	4.96%	57.2	79.4

DISCUSSION

In this study, the thicknesses of HVL layers, are calculated, using EGSnrc simulation codes, and measured, using an empirical method at different energies (120 and 180 kVp), then, are compared with each other. In the empirical method, the absorption curves were employed for measuring the HVL. At first, these curves were drawn, by fitting a third grade equation over the points at which the transmitted exposures through the attenuation layers have been measured.

By interpolation over the drawn curves, the HVLs (i.e., points at which the intensity of the exposure reached to half of its original value) are derived at different energies.

The EGSnrc based BEAMnrc and DOSXYZnrc from the National Research Council of Canada (NRCC) group were used in this study (19). The EGSnrc was developed from the EGS4 code (11). The EGS (Electron–Gamma–Shower) system of computer codes is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several hundreds of GeV (13). The EGSnrc-based BEAMnrc code (20, 21) was used to simulate the geometry of the head of the machine and the BEAMDP code was used to derive the X-ray spectra at different energies and determining of the HVL (4, 12).

In the previous studies the HVL index was evaluated using different experimental methods and also simulation codes (e.g., PENELOPE). Mainegra *et al.* (4) proposed two methods for calculating the HVL, that were in good agreement with experimental results (i.e., 2.3% differences at most). Chica *et al.* (3) in their study calculated the HVL by the PENELOPE code, which showed about 2% difference with the experiment. Another method for the evaluation of the X-ray beam quality was proposed by Chica *et al* (3) in which the ratio of absorbed dose in $Z_{1/2}$ and $Z_{1/4}$ depths (which are the depths in water at which the dose is 50 and 25% of the dose at Z_0) were measured and compared with those obtained by simulation (PENELOPE). From the simulated and measured depth dose curves they have evaluated the corresponding $Z_{1/2}$ and $Z_{1/4}$. As for the quality indices, no statistical differences between experimental and simulated results are observed, and both the $Z_{1/2}$ and the $Z_{1/4}$ obtained from the experimental curves are in reasonable good agreement with the simulated ones. The comparison between simulated and experimental results showed a very good agreement (at most 3%).

The practical worth of this study is applicability of this method in radiotherapy departments with limited lab instruments. In this study, comparison between the calculated and measured HVL values (table 1) showed that the highest and lowest differences between the two are 4.96% and 2.27%, respectively, which are in fairly good agreement with those obtained in the former studies. These differences were lower than those obtained in other studies (22, 23).

CONCLSION

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 empirical method can be employed as a routine clinical test tool for every radiotherapy department, especially in those with limited lab instruments.

Conflict of interest: *Declared none.*

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