Monte Carlo modeling of a X-ray tube for superficial radiotherapy for evaluating the beam quality and the depth-dose distribution

Smolin Sergei1,2 a), Butorov Ilya3, b) and Shevchenko Elena1, c)
1Irkutsk State Medical University, Irkutsk
2Irkutsk Regional Cancer Center, Irkutsk
3Joint Institute for Nuclear Research, Dubna

a)Corresponding author: millennium_s@mail.ru
b)butorov.ilya@gmail.com
c)kalasha.50@mail.ru

Abstract. The purpose of this study was to evaluate the possibility of using GEANT4 modeling package in the problems of dosimetry and treatment planning of superficial radiotherapy on the apparatus "Roentgen TA-02". Experimental measurements and calculation of half-value layer for beams in the regular operation modes, as well as depth dose distributions were carried out in accordance with the recommendations of American Association of Physicists in Medicine (AAPM). These parameters were compared with the results of the computer model of the x-ray tube. Comparison of partial half-value layer showed high efficiency of GEANT4 package in processing of physical processes associated with x-ray radiation and interaction with the matter. The data obtained during the work with the x-ray tube model are comparable both with the estimated results and published by other authors. The x-ray beams obtained in the simulation is comparable in quality with the real ones. The simulated and real beams coincide with the depth-dose distribution in the tissue equivalent medium with high accuracy.

1.Introduction

One of the priority areas for increasing the effectiveness of radiotherapy is an improvement of the dose calculation algorithms used in radiation treatment planning. The accuracy of the dosimetric planning calculations depends on the type of irradiated tissues, its density and the presence of heterogeneities [3]. The model of the radiation source used in the calculation is equally important too. The development of programs that optimized for calculations in radiotherapy problems and the improvement in computer processor technology have made possibility to reduce the calculation time in clinical cases. Thanks to the efforts of several research groups, algorithms for calculations of radiation interaction in matter using the Monte Carlo method have been developed. These algorithms, such as PENELOPE, GEANT4, PTRAN and FLUKA, are used in the fields of medical physics and dosimetry. However, in cases of planning the superficial radiotherapy, manual calculation is often used. This method of radiation therapy has not received due attention in the form of the development of computer treatment planning systems [5]. As noted by some authors, the availability of a reliable tool for
evaluating the characteristics of X-ray machines would be very useful in clinical practice [11,12,13,16]. In addition, it was noted in [6,15,18] that it is important to take into account the influence of heterogeneities of the irradiated volume on the interaction of X-rays, which is not taken into account in manual calculation.

An important step in the clinical application of Monte Carlo algorithms for dose calculation in the treatment planning is experimental verification. There are a number of publications, the authors evaluated the adequacy of the computer models of X-ray tubes by comparing various physical parameters. Thus, in the study of Guimarães C.C., Moralles M., Okuno E. [7], the values of the mean energy and the half-attenuation layer (HVL) were compared with their own experimental data and with the reference values given in ISO [20]. The authors of another paper [13] compared the experimentally measured spectrum of the «Philips MG450» X-ray tube with the model data created in the GEANT4 package. From the clinical point of view, the surface dose is the most important quantity in the quality assurance of X-ray therapy [18,19]: in the study [14], a surface dose was evaluated using irradiation with X-rays and gamma radiation from a Co-60 radioisotope using thermoluminescence detector (TLD) models.

The values of the first and second half-value layers (HVL), the beam homogeneity factor, and the energy distribution of the radiation (spectrum) are important physical characteristics of X-ray tubes [6,17]. In turn, the surface dose and the depth-dose distribution are of clinical interest, and these data are necessary in treatment planning in a specific clinical case [9,11,12,15].

Modeling of X-ray tube in any package based on the Monte Carlo method involves a number of difficulties. First of all, it is necessary to decide how close to reality will be the structure of the model. In some studies [7,13], the design of the tube was reduced to modeling the electron beam incident on the tungsten anode (molybdenum - in the simulation of diagnostic X-ray tubes) located at a certain angle to the direction of incidence of the beam (the angle was determined by the design of the tube). The beam of photons received as a result of interaction with the target passed through the beryllium filter, and through additional filters from aluminum; then the beam got on the irradiated volume serving as a detector. One of the drawbacks of such models is the absence of air in the region between the exit window of the tube and the detecting volume, which influences the low-energy part of the spectrum in real clinical conditions. An important role is played by tubes (unique for each particular model of the apparatus), which are a system for forming a radiation beam. A more accurate model of the X-ray tube created with the EGSnrc package [8] includes the tube body itself, additional diaphragms (a feature of the simulated tube) and a forming device (called tube or applicator).

In this study we investigate the effectiveness of the GEANT4 package in calculation of physical processes associated with the production of X-rays and its interaction with matter. In the course of the study, such parameters of the superficial radiotherapy device «Roentgen TA-02» (Figure 1) as a half-value layer (HVL) and the depth-dose distribution in the irradiated volume were compared.
2. Materials and methods

In this study we used the GEANT4 package version 10.03 to create a model of «1BTV4-100» with a lateral radiation output used in superficial radiotherapy devices «Roentgen TA-02» and «RUM-21». The tube body is made of stainless steel and lead, the anode is located at an angle of 45 degrees. The model includes a beryllium window, secondary aluminum filters of various thicknesses and forming brass tubes (applicators) of various shapes. The X-ray spectra were calculated using the Monte Carlo method based on the Livermore libraries describing low-energy photon radiation. The simulation was carried out in two stages.

In the first stage, a beam of primary particles (electrons) interacts with the tungsten anode of the X-ray tube, giving rise to bremsstrahlung and characteristic radiation. Calculations were carried out on a PC (Intel Core i5, 2.5 GHz) using $10^8$ primary electrons. Further, the resulting radiation interacted with a layer of beryllium simulating intrinsic filtering of the tube and an aluminum layer serving as an additional filter.

At the second stage, the interaction of photon radiation with phantoms of various configurations was simulated to obtain data on the quality of radiation and depth-dose distributions.

Data on beam quality and depth-dose distribution were experimentally obtained and calculated for standard operation modes of the tube «1BTV4-100» on the superficial radiotherapy apparatus «Roentgen TA-02» on the basis of the Irkutsk Regional Cancer Center (Table 1).
2.1 Half-value layer
According to the guidelines for dosimetry of low-energy photon radiation, the quality of the beam should be determined by the value of the half-value layer (HVL), which is defined as the thickness of the standard absorber necessary to reduce the beam intensity (dose rate in air) by half from its initial (without filtration) value [4]. The concept of a second HVL is also used - the difference between the thicknesses of a standard absorber, resulting in a fourfold and twofold reduction in the dose rate in the air. The ratio of these two quantities - the ratio of the second half-attenuation layer to the first one is called the beam homogeneity factor, (in the foreign literature, the beam homogeneity factor is the inverse ratio - the first half-value layer to the second) [2].

Experimental measurements of the half-value layers were carried out in accordance with the recommendations of the American Association of Physicists in Medicine (AAPM) - using a set of high-purity aluminum filter plates from 0.05 to 2.96 mm Al. Based on the data on the selection of a suitable applicator, described in [11], an applicator with a diameter of 3 cm was chosen. This ensured the minimization of the contribution of the scattered radiation. The aluminum plates were mounted on a stand close to the applicator. The ionization plane-parallel chamber PTW-Freiburg 23342 with a sensory volume of 0.02 cm³ was set at a distance of 100 mm from the edge of the applicator, according to the recommendations [1.10], after which the dose rate was measured.

In computer model of the tube at a distance of 100 mm from the edge of the applicator, a silicon detector measuring 10x10x10 mm was mounted on the central axis of the beam. At the edge of the applicator were installed layers of aluminum with an area of 100x100 mm of different thicknesses (specified in the model parameters - from 0.05 to 10 mm Al). As a result of the work of the model, the value of the dose absorbed by the detector was output.

Based on the detector measurements, the first and second half-value layers were calculated by inverse linear interpolation on a semilogarithmic scale using the formula:

\[
HVL = x_1 + \frac{(ln(D_0/2) - lnD_1)(x_2 - x_1)}{(lnD_2 - lnD_1)}
\]  

(1)

where \( x_1 \) and \( x_2 \) are the thicknesses of the absorber, between which lies the value of the HVL; \( D_0 \) - value of dose rate without absorber; \( D_1 \) and \( D_2 \) - values of dose rate with absorber of thickness \( x_1 \) and \( x_2 \) [2].

On the basis of calculated values of the half-value layers, the beam homogeneity coefficient was calculated for all operation modes.

2.2 Depth-dose distribution
For the measurements of depth-doses we used a plate solid-state phantom PTW Soft X-Ray Slab Phantom with an adapter plate for the plane-parallel ionization chamber PTW-Freiburg 23342 and UNIDOS-E Universal Dosemeter (PTW, Freiburg). Experimentally, the distribution of the absorbed dose in the water-equivalent medium was measured by successively adding Soft X-Ray Slab Phantom plates over the adapter plate with an ionization chamber fixed in it. The dose was measured in steps of 1 mm.

In the computer model, the depth-dose distribution was determined using the Monte Carlo method. A phantom of polymethylmethacrylate (PMMA: density 1190 kg/m³, H - 8.06%, C - 59.98%, O - 31.96%), consisting of 200 plates measuring 100x100x1 mm, was placed close to the edge of the applicator. After passing the X-ray radiation through the phantom, a series of values of the absorbed dose in each of the plates was plotted.

The value of the half-dose layer (HDL), usually used in the planning of superficial radiotherapy, was calculated with the help of formula (1). The half-dose layer is equal to the thickness of the tissue-equivalent material, which attenuates the beam by a factor of two with respect to the value on the surface. In these calculations, the values of \( x_1 \) and \( x_2 \) were the thicknesses of the solid-state phantom.
between which the value of the HDL lies; D₀, D₁ and D₂ are the dose rate values on the surface of the phantom and at the depths x₁ and x₂, respectively.

3. Results

The data obtained as a result of the experiment and simulation were subjected to statistical processing. The standard deviation of calculated values was estimated. Ten measurements were taken for every point both in experiment and simulation.

3.1 Half-value layer

The Table 2 shows the results calculated on the basis of experimental data and data from a computer model. The error in determining the half-attenuation layer is indicated in parentheses.

**Table 2.** The results of calculating the values of the first and second half-value layers (HVL₁ and HVL₂) and the beam homogeneity coefficient

| № | Energy (kVp) | HVL₁, mm Al | HVL₂, mm Al | Beam homogeneity coefficient |
|---|---------------|-------------|-------------|-----------------------------|
|   |               | Experiment  | Simulation  | Experiment  | Simulation  | Experiment  | Simulation  |
| 1 | 30            | 0,19 (0,01) | 0,2 (0,01) | 0,29 (0,01) | 0,3 (0,02) | 0,66        | 0,67        |
| 2 | 40            | 0,53 (0,02) | 0,55 (0,02) | 0,83 (0,02) | 0,84 (0,02) | 0,64        | 0,65        |
| 3 | 60            | 1,25 (0,02) | 1,2 (0,02) | 1,95 (0,03) | 1,9 (0,03) | 0,64        | 0,63        |

3.2 Depth-dose distribution

Figure 2 shows the depth-dose distributions for all standard modes of operation of the superficial X-ray therapy apparatus, obtained experimentally and using the X-ray tube model. Table 3 shows the calculations of the half-dose layers. The error in determining the HDL is indicated in parentheses.

**Figure 2.** Depth-dose distributions for the standard operating modes of the apparatus, obtained experimentally and based on simulation results
4. Discussion

There is a good agreement between the values of the half-value layers obtained in the present study in the 30 and 60 kVp operating modes with those published in [2], where these regimes were also studied for superficial radiotherapy device "Roentgen TA-02". According to the criteria of ISO 4037-1 [20], if HVL₁ and HVL₂ in current material are within 5% for two X-ray beams, these beams can be considered equal in quality. Differences between the experimental and simulation data show that the results of work in the GEANT4 package can be considered adequate - the radiation beam created in the model is equal in quality to the real one. As can be seen from the presented graphs and calculations of the half-dose layer for each of the operating modes, the model provides a coincidence with the experimental data and from the point of view of interaction of the obtained radiation beam with matter.

5. Conclusions

A computer model of the X-ray tube «1BTV4-100» is developed on the basis of algorithms for calculating the generation and interaction with matter of low-energy X-rays, which are incorporated in the GEANT4 software package. The efficiency of the GEANT4 package was tested in processing physical processes associated with the production of X-rays and its interaction with matter. The developed model of the generating source of ionizing radiation can be used as a basis for the radiotherapy treatment planning system for superficial X-ray therapy.

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### Table 3. The results of calculating the values of the half-dose layers (HDL)

| №  | Energy (kVp) | HVD, mm of tissue-equivalent material |
|----|--------------|--------------------------------------|
|    |              | Experiment | Simulation  |
| 1  | 30           | 3.07 (0.02) | 3.13 (0.02) |
| 2  | 40           | 7.67 (0.03) | 7.78 (0.03) |
| 3  | 60           | 12.58 (0.03) | 12.88 (0.03) |
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