Computational Model, Energy Spectra and Assessment of 7MeV, 9MeV and 11 MeV Electron Beams Emerged from Neptune 12PC Linear Accelerator Using Monte-Carlo Simulation Method: A Theoretical Study

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Abstract— The electron beams are widely used in radiotherapy. As the nominal energy of electrons is not sufficient to create suitable electron beams for remediation purposes, it is necessary to determine and use the dose data in depth for electron beams. The goal of the current research is to obtain the dose data in depth for 7MeV, 9MeV and 11 MeV electron beams emerged from Neptune 12PC linear accelerator and to assess the characteristics of the beams using Monte-Carlo simulation method. In this research, BEAMnrc code was used to simulate the considered accelerator. In addition, DOSXYZnrc code was applied to model the water phantom (RFA300). The profile of dose in depth along the central axis (percent depth dose) and its perpendicular axis (beam profile) was depicted for these electron beams in a 10×10 cm^2 field using Monte-Carlo method. The R_{100}, R_q, R_{85}, R_{50} and R_p depth dose parameters were obtained from normalized profiles of dose in depth. The calculated profiles of dose in depth along the central axis and its perpendicular axis are of very good agreement with experimental profiles. Since different accelerators with similar manufacturer and model frequently have similar structures, it seems that the computational model of other accelerators from the same manufacturer can be accessible by simulating one of them and by changing the energy spectra and beam quality indices of simulated beams. Moreover, using the computational model of any accelerator, it can be possible that the effect of every remediation structure of accelerator on the electron beams is evaluated and finally, the resulted dose distribution is obtained and evaluated.

Index Terms— Monte-Carlo method, Medical linear accelerator, Electron beam, Radiotherapy, Simulation, Computational model, Energy Spectra

1 INTRODUCTION

The electron beams in the energy range of 4-50 MeV are widely used in radiotherapy [1]. These beams are used for treatment of head and neck cancers to protect the spinal cord from radiation and for treatment of chest to limit radiation to lung [1]. As the nominal energy of electrons is not sufficient to create suitable electron beams for remediation purposes, it is necessary to determine and use the dose data in depth for electron beams [2-12].

The Monte-Carlo method is a statistical simulating method for radiation transport cases [13, 14]. It can be possible to accurately model the effective physical processes in radiotherapy with any complicated geometry using this method [15]. It is widely accepted that the Monte-Carlo simulation of radiation transport is one of the most accurate methods for describing the distribution of attracted dose in radiotherapy [16-27]. Particularly, the reflected radiations from materials with high density, such as bone, or dispersion turbulences induced by air voids can be considered by Monte-Carlo simulation with higher accuracy than any other available model [28, 29]. However, the Monte-Carlo calculations should be experimentally confirmed [30]. The main problem of Monte-Carlo method is its extensive calculations which are not important anymore because of rapid growing of fast and cheap computers and of applying of new variance decreasing methods [31, 32]. The Monte-Carlo simulation is rapidly going to be the next generation of dose calculation machine in prevalent clinical radiotherapy systems [33, 34].

The application of Monte-Carlo method in simulating of electron beams has a long time history [35-49]. In first years, complete simulating of accelerator geometry was very difficult mainly due to low speed of computers and simplicity of available Monte-Carlo codes [50-61]. This complicated problem was firstly solved by Udale / Udale-Smith, who was extensively coded the problem (about 18000 line in FORTRAN) based on the EGS4 system code [62-64].

In addition to Udale-Smith work and developing of BEAM system by Rogers et al. [65], more works have been done for complete simulating of medical electron accelerator [66-70]. Generally, the Monte-Carlo method is suitable for electron dose calculation in all conditions [71]. The simulated beams can be used to calculate the dose distribution in phantoms or patients [72-75]. However, the Monte-Carlo calculations should be experimentally verified [76-90]. In the current re-

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search, the dose data of electron beams resulted from 12PC Neptune linear accelerator in depth is obtained by Monte-Carlo simulation and the characteristics of these beams are evaluated.

2 MATERIALS AND METHODS

2.1 Monte-Carlo Simulation

In the current research work, the BEAMnrc code, which is based on the EGSnrc Monte-Carlo code, is used for simulating the 12PC Neptune linear accelerator in ((electron mode and electron transport)). This code is suitable for simulating of three electron modes and photon mode of medical linear accelerators [75]. In order to model the considered accelerator, the information about the geometry and material and composition of materials in different parts of accelerator was obtained from manufacturer. Then, the head therapy structures of accelerator were modeled as component modules (CMs). The concept of CM was used in Udale-Smith code [76]. In BEAM code, this method developed and played an important role [77]. CMs are various types of geometrical elements which are possible to be used for explaining the structures of an accelerator. In the current research, the following actions were performed to simulate the considered accelerator by BEAMnrc code:

- Selecting of necessary CMs for defining of accelerator's structures.
- Selecting the library of used data for defining the materials in simulations.
- Defining the main input parameters such as: type of radiated particle, characteristics of radiating source (beam energy and its distribution), number of particles needed for transportation, cut-off energy of particles, calculating the total dose or related dose to different structures, number of recording levels, position and measure of recording levels and related parameters to EGSnrc code, such as related algorithms to particles transport.
- Defining the related parameters to any CM.
- Compiling the simulated program for considered accelerator.
- Correcting the present errors.
- Running the compiled program in BEAMnrc code.
- Deriving the necessary information from the output of code.

Ten files are emerged in output of BEAMnrc code. The main file in the output has suffix of egslst which is including the all results of dose and flux of simulation. In addition, a summary of main input parameters, information related to CMs, applied materials and so on are presented in the output file.

Another important output file of BEAMnrc code is the phase space file which its suffix is egsphsp1 (2 or 3). This file includes all information of phase space for all particles passing through the recording level (information of position, direction and energy). This file can be used as a source in input of dose calculation code (DOSXYZnrc). The DOSXYZnrc code simulates the path of source particles within the cells or defined vessels with various density and composition in a phantom. It allows defining the source with various geometry and energy. In addition, the obtained phase space files from output of BEAMnrc code can be used as the source in DOSXYZnrc code. In this code, the parameters of cut-off energies for electron transport and photon transport and threshold of electron production (AE) and photon production (AP) were selected similar to BEAMnrc code, which are thoroughly described in the verification part of the simulated program. The PRESTA-II algorithm was used to electron transport in all of simulations with BEAMnrc and DOSXYZnrc codes. The calculated dose distributions by DOSXYZnrc are available in output files with suffixes of egslst, 3ddose and pardose. The file with suffix of egslst is the most important output file. This file is not only including the dose data and statistical calculations, but also is including the information about the simulated geometry, number of histories and running duration of the program for simulations.

In the current study, a computer with double core CPU (ADM Athlon™ 64*2) and 3800 GHz frequency of process and 1 GB RAM with Windows XP® as operating system is used for simulating.

2.2 Experimental Measurements

The experimental measurements in the current study are performed based on the TRS-398 protocol of International Atomic Energy Agency (IAEA) [13]. The following tools are used in this step of study:

This accelerator is controlled by a computer and hence, PC is mentioned next to its model. All performance of controlling systems is controlled by micro-processors. Its electron gun is semi-conductive and exited electrons are of 40-45 keV energy. In this research, the considered accelerator electron mode is used. The accelerator is able to produce electron beams with 7 MeV, 9 MeV and 11 MeV energies in this mode. The maximum dose rate in this mode is 300 MU/min in homocentric distance and in maximum depth of dose. It should be mentioned that 50, 100 and 200 MU/min can be selected depending on the case. The size of remedial field in electron mode is determined by applicators. By definition, khan is attributed to the fields smaller than reference field (10×10 cm^2) and the fields with larger size than reference field named as large fields [14].

The water phantom type RFA-300 with dimensions of 50×50×50 cm^3 was used in this study. This phantom is made from Plexiglas and is one of the standard tools in dosimetry systems of accelerators which are used in daily measurements, quality control and so on. Various types of gassy and semi-conductive detectors can be mounted on this water phantom. Displacement of detectors within the phantom can be controlled by operator (hand-control) or computer (automatic control).

The semi-conductive detectors, or diode detectors, are rigid state tools for dose measurement which are often made from silicon [78]. A waterproof silicon diode of type P with thickness of silicon chip equal to 0.5 mm and 2 mm diameter of sensitive region was used for measurements. In addition, a diode detector was placed around the radiation field as reference detector during measurements.

As the ratio of silicone power stop to water power stop is

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rarely varied with energy change in the range of 1-20 MeV (about 5%), the measurement with diode can be directly used to obtain the dose distribution in depth [79].

A software package named as Scanditronix RFA plus was used for dosimetry in Neptune accelerator. Relative dosimetry, absolute dosimetry and quality control of accelerators are possible with this software [80]. The software is compatible with ((Microsoft Windows)) and its measurement steps are performed in graphical environment. The software has the most of dosimetry protocols.

As mentioned in previous sections, the current study aims to evaluate the electron beams resulted from 12PC Neptune linear accelerator using Monte-Carlo method. To do this, the considered accelerator was firstly simulated using BEAMnrc Monte-Carlo code in the reference field (10×10 cm^2) and for 7 MeV, 9 MeV and 11 MeV energies. The attracted dose of a 50×50×50 cm^3 water phantom was simulated by DOSXYZnrc Monte-Carlo system which is based on EGSnrc Monte-Carlo code, similar to that was performed in experimental measurements. To calculate the profile of dose in depth, some detectors of 2×2×0.2 cm^3 was defined within the simulated phantom so that the center of detectors was along the central axis of electron beam.

To provide a 5 cm air gap between lower part of applicators and body surface of patients, all of Monte-Carlo calculations and experimental measurements was performed in SSD of 105 cm. The physical parameters of input file of simulation code including the source parameters, cut-off energy of radiations, radiation transport algorithm and so on were suitably chosen in considered simulations. As low energy electrons have a little contribution in phantom dose in radiotherapy, the cut-off energy of electrons can be considered higher to reduce the running time of calculations [81]. Hence, in all simulations, the cut-off energy were considered as 0.8 MeV and 0.01 MeV (its common value) for electron transport (ECUT) and photon transport (PCUT), respectively. Further, 521ICRU data library was used for simulating in the current study. The corrections of density effect based on the ICRU recommendations are considered in this data [82]. In order to provide a suitable statistics in calculations of attracted dose, number of source electrons was considered as 60 million which led to average relative error equal to 0.5%. The time required to run the program so that this error is reached was about 10.6 and 13.12 hours for 7 MeV, 9 MeV and 11 MeV electron beams, respectively, by the computer used in this study. For calculations of dose in depth, the particles were transported in the accelerator, which was modeled with BEAMnrc code, at first, and after each transport, information of every particle (position, direction and energy) was saved in a phase space file. The size of the phase space files obtained from running of 60 million particles was 93.9 MB and 166 MB for 7 MeV, 9 MeV and 11 MeV electron beams, respectively. Then, this information was used as input data to DOSXYZnrc system for calculations of dose in depth.

In most of previously performed studies in this field, the initial electron source has been considered as a single energy, point source on the central axis of radiation [83]. In this study, the energy and angle distribution of electrons for initial electron source was obtained by trial and error. To do this, initial electron sources with following characteristics was used:

(a) Single energy point source located on the axis.

(b) Point source with Gaussian energy distribution located on the central axis with FWHM equal to 5% of most probable energy.

(c) Single energy pencil beam sources with diameters of 2 an 4 mm on the central axis.

(d) Pencil beam sources located on the central axis with diameters of 2 and 4 mm and with Gaussian energy distribution and with FWHM equal to 5% of most probable energy.

Then, the profiles of dose in depth for considered sources were calculated and compared to experimental measurements and finally, the suitable initial electron source with was selected by compatibility of measured and calculated R50 obtained from tested sources for three energies [84, 85].

Therefore, in the current research, initial electron pencil beam sources with diameter of 2 mm and 6.4 MeV and 8.42 MeV single energies, located on the central axis of radiation, were used for Monte-Carlo simulations of 7 MeV, 9 MeV and 11 MeV electron beams, respectively. As a result, percent depth dose and beam profiles in the reference field and in the simulated water phantom, for two considered accelerator energies which have similar structural characteristics, were calculated. In addition, these profiles for similar cases were experimentally measured in RFA300 water phantom using diode detectors.

To verify the simulated model, the measured and calculated dose profiles were compared to each other. Finally, the characteristics of electron beams resulted from above accelerator, including: Normalized maximum depth dose (R_{100}), the depth in which tangent line on the slope of curve crossed the line passing thorough the maximum dose (R_q), depth of 85% dose (R_{85}), depth of 50% dose (R_{50}) and depth of practical range of electrons (R_p), in the reference field and for three considered energies were evaluated.

Moreover, empirical equations governed on the beam characteristics for average of energy (E_0) and most probable energy (E_{p0}) were evaluated from calculated and measured values.

3 RESULTS AND DISCUSSION

The recorded values after the practical range of electrons, which is related to dose induced by produced photons in the path of electron beams within accelerator and water phantom, are negligible in both experimental and computational methods due to low energy of electron beams.

In BEAMnrc code, it can be possible to calculate three quantities of deposited energy (EDEP) and attracted dose, totally and in each structures of accelerator. In the current study, the attracted doses in the defined cells within the water phantom were obtained for calculations of percent depth dose and beam profiles.

The attracted dose was calculated by EDEP parameter which is the deposited energy in each cell in terms of Joules. Then, the obtained value of energy in each cell was divided by its mass in terms of kilograms and the attracted dose was resulted in terms of Grey.

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The values of parameters related to measured and calculated percent depth dose for electron beams with 7 MeV, 9 MeV and 11 MeV energies. As previously mentioned, each experimental value is the average of three measured values. In addition, the statistical error in calculation of parameters using Monte-Carlo method is lower than 1%. It can be seen that there is a good agreement between parameters in both methods. It can be seen that the calculated profiles are symmetric similar to the measured ones, which confirms the symmetry of simulated geometry.

The Kolmogorov-Smirnov statistical test was used to compare the measured and calculated values. The P-value obtained from this test for percent depth dose is 1.0 for 7 MeV, 9 MeV and 11 MeV while for beam profiles this value is 0.416, 0.759 and 10.371 for 7 MeV, 9 MeV and 11 MeV energies, respectively. It can be observed that the dose measured amounts are in good agreement with calculated ones in all profiles so that the maximum error for each data point on the profiles is as small as 2-3%.

Based on the TRS-398 protocol of IAEA, R_{50} is used to determine the quality index of electron beams [86-90]. So, adjusting of R_{50} values from the measured and calculated (by Monte-Carlo method) data and good agreement between percent depth dose and beam profiles are a confirmation on the verification of the simulation method and the simulated model.

4 Conclusion

Manufacturers define the energy spectra of electrons before the output window. As a result, the recorded energy spectra in the output of accelerator are differing from the input spectra to some extent. The nominal energy of electron beams, acclaimed by manufacturers, is not sufficient for a suitable electron beam for remedial actions. Therefore, dose data in depth should be determined for clinical beams and they should be used. In addition, the characteristics of initial electron beams are not available in most of accelerators and at the other hand, the setting of accelerators during mounting are different. So, it can be possible that different accelerators with same model and same manufacturer have different dose distribution and therefore, one of the best effective methods to determine the characteristics of electron beams (angular and energy distributions) is Monte-Carlo method. Using this method, three energy spectra of electron on the output of accelerator and the effect of every remedial structures of accelerator on the energy spectra and then, the resulted dose distribution, can be easily obtained. Regarding that different accelerators from a manufacturer and with similar model have similar structures, it can be said that the effect of these structures on the electron beams in accelerators with same manufacturer and same model will be similar. As a result, the only unknown parameter is the real energy of electron beams at the time of setting. Therefore, if one of these similar accelerators is modeled using Monte-Carlo method as reference accelerator, and the energy spectra and quality index of its electron beams are determined by Monte-Carlo method, finally, the computational model of other accelerators from that manufacturer will be at hand, without further simulating of each accelerator, only by varying the energy spectra and quality index of reference electron beams. Generally, the results of the current study show that a computational model of the electron mode from the considered accelerator will be obtained using the information from 12PC neptun accelerator and BEAMnrc simulating code.

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