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Monte Carlo Study of Photon Dose Distributions Produced By 12 MV Linear Accelerator

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Abstract

BEAMnrc is a Monte Carlo code for simulation of photon and electron transport in the radiotherapy field. The purpose of this paper was to develop a technique to derive best estimates for the energy and intensity distribution of the incident electron beam by comparing calculated and measured values for the linear accelerator Saturne 43 machine. We varied the initial electron energy and full width half maximum of the radius of the electron beam incident on the tungsten target to find the percentage depth dose, dose profile curves, the tissue-phantom ratio $TPR_{20/10}$, the energy fluence distribution and angular distribution for a square field size 10 × 10 cm^2. It is found that our results were quantitatively in good agreement with experimental PDD and lateral profiles at 10 cm depth. The $TPR_{20/10}$ was agreed well with the literature publisher works. Furthermore, we could reduce the discrepancy between measured and calculated data photon dose distributions to 1.5%/1mm in the gamma index method for the energy 11.8 MeV and full width half maximum equal to 0.07 cm. Monte Carlo simulation of the treatment head of the Saturne 43 machine was successfully done changing the initial properties of electron source in the Monte Carlo BEAMnrc code. That shows the efficacy and accuracy of the technique used in this paper.

Keywords: Monte Carlo; Photon dose distribution; BEAMnrc; Tissue-Phantom Ratio;

Introduction

Cancer is the principal cause of death globally. The International Agency for Research on Cancer (IARC) recently estimated that 7.6 million deaths worldwide were due to cancer with 12.7 million new cases per year being reported worldwide [1]. External beam radiation is delivered by aiming high-energy rays (photons) to the position of the tumor to destroy cancer cells [2-5]. The evolution of external radiotherapy techniques allows an improvement in the development of the treatment plan. This stage consists in defining in a sophisticated way all the irradiations that will have to be applied to the patient in order to completely destroy his tumor, made up of cancer cells. Clinical application of such techniques requires reliable estimation of the absorbed dose distributions to sufficiently irradiate the cancerous tissue. Patient dosimetry then becomes the stage where treatment planning can be calculated, evaluated, verified experimentally and finally validated.

MC (Monte Carlo) techniques are the reference tool for precise dose calculations and their accuracy has been fully quantified in the literature [5-9]. Researchers and clinicians used the MC simulations to test the accuracy of the computation dose for the Treatment Planning Systems (TPS) in the simple geometry as water phantom geometry.

In the last years, MC techniques can be used in the dosimetry and TPS using the last development of computer technology. Photon beams parameters generated by linacs as percentage depth dose, profile dose, mean energy, and others factors show differences between manufacturers and may be seen also by the same manufacturer. There have been many works of MC techniques in the simulation of the linacs machine (Varian, Elekta, Siemens, Philips…) defining the influence of initial electron beam parameters for radiotherapy photon beams. Verhaegen and Seuntjens, [5] used the mean energy of 6 MeV and the FWHM (Full Width Half Maximum) electron spot of 0.2 cm. Sheikh-Baghri and Rogers, [6] simulated the Siemens KD, Varian Clinac, and Elekta SL25, they altered the energy in steps of 0.1 MeV over a range from 5.5 to 6.6 MeV and varied the radius from 0.01 to 0.19 cm. Tzedakis, et al. [7] varied the energy by step of 0.2 MeV from 5 to 7 MeV for the Philips/Elekta SL75/15 and altered the radius from 0 to 0.40 cm in steps of 0.02 cm. Pena, et al. [8] studied the Siemens PRIMUS and Varian 2100 CD, they use increments of 0.25 MeV over an energy range of 5.5 to 6.5 MeV and used the radius 0.05 cm over a range from 0.05 to 0.4 cm. Other works such as that by Sawkey and Faddegon, [9] for the Siemens ONCOR machine more precisely studied the source parameters based on additional measurements of non standard characteristics. Mohammad Taghi Bahreyni Toossi, et al. [10] used the mean energy of 6 MeV and the FWHM electron spot of 0.2 cm. Recently, Bakkali J, et al. [11] have studied the Saturne 43, the initial electron energy is altered by steps of 0.1 MeV over an energy range of 11.3 to 12.3 MeV and has fixed the value of FWHM = 0.117 cm. Our aim in this paper was to study the properties of initial electron beams and comparing calculated and experimental values obtained at the French National Metrological Laboratory for ionization radiation of the Saturne 12 MV linac. For this purpose, we have changed the energy from 11.4 to 12.2 MeV by steps of 0.1 MeV and FWHM from 0.03 to 0.19 cm by steps of 0.02 cm to obtain a good agreement between BEAMnrc and experimental results.

Materials and Methods

Experimental Data

The experimental dosimetric data are carried out in the laboratory NHLB (National Laboratory Henry Bequerel) in France [12]. These dosimetric data include PDD (percentage depth dose) (the dose along the beam axis), and the DP (dose profile) (measured at 10 cm depth of the tank) are measured in a water cubic tank with a dimension of 40 x 40 x 40 cm^3 on a PTW-3100 cylindrical ionization chamber [12]. The entrance surface of the water cubic tank is placed with a distance of 90 cm from the tungsten target. The generation of a square field must be with a dimension of 10 x10 cm^2 in 100 cm from the target. It is recommended that water should be the reference medium for dosimetry in radiotherapy because the biological tissues consist of more than 80% of water.

Monte Carlo Simulation

The electrons are incident on a tungsten target producing bremsstrahlung photons which are collimated by the linac head component. In this study, the MC simulation was performed using the BEAMnrc and DOSXYZnrc codes running in Linux system. The process of calculating the dose distribution in this work was divided into two steps. First, the BEAMnrc user code was employed to transport the photon and electron from the target to a predefined scoring plan positioned at the depth of z = 41.25 cm below the jaws where particles were written to a Phase Space File (PSF). In the second step, the PSF obtained in the first step was used as a source on the DOSXYZnrc user code where particle were transported through a 40 × 40 × 40 cm^3 water phantom.

Modeling of Saturne 43's head geometry with BEAMnrc

In this study we simulated the head of Saturne 43 completely based on the manufacturer's detailed information. The head of Saturne 43 linac (linear accelerator) was modeled as show the figure 1 which consists of different components: a titanium window and a target of tungsten with a thickness of 4 mm used to produce photon primarily generated by bremsstrahlung interactions between the incident accelerated electron and the target; a primary collimator modeled by the intersection of a cylinder and a cone of composite material WNiCu (W, Ni, Cu), and XC10 (C, Mn, Fe) to limit the dose to the maximum usable field size; a flattening filter consists a set of cones, and cylinders: the flattening filter has a height of 4.6 cm and its base is confused with a cylindrical support of 0.65 cm in height and a radius of 5.4 cm. The cone and its support are made of stainless steel. The flattening filter is inserted in a collimator of conical lead shape. The flattening filter was used to generate a beam of uniform intensity; a monitor unit chamber of Kapton; a plaque of aluminum; and finally a component of X and Y pair jaws that are composite from mixture of materials WNiCu, XC 10, and Pb, the apertuture of the filed size needed was controlled by that pair of jaws.

BEAMnrc is a MC simulation system (Med. Phy. 22, 1995, 503-524) for modeling radiotherapy sources which was as part of the OMEGA project to develop 3-D treatment planning for radiotherapy (with the university of Wisconsin) and is considered a reference MC code in the field of radiotherapy . The BEAMnrc code was used to model the transport of electrons and photons in the geometry of the head of linac according to the manufacturer's data. We used the Source number, ISOURC=19 with Gaussian distribution in the x and y plane with origin on beam axis from FWHM = 0.03 cm to FWHM = 0.19 cm by step of 0.02 cm. The initial histories were 3 × 10^9 particles. The energies was changed from 11.4 MeV to 12.2 MeV by step of 0.1 MeV and the field size 10 × 10 cm^2 was performed for all the simulations. The electron energy cut-off was 0.521 MeV, while photons were transported down to energy of 0.01 MV [Cut: P].

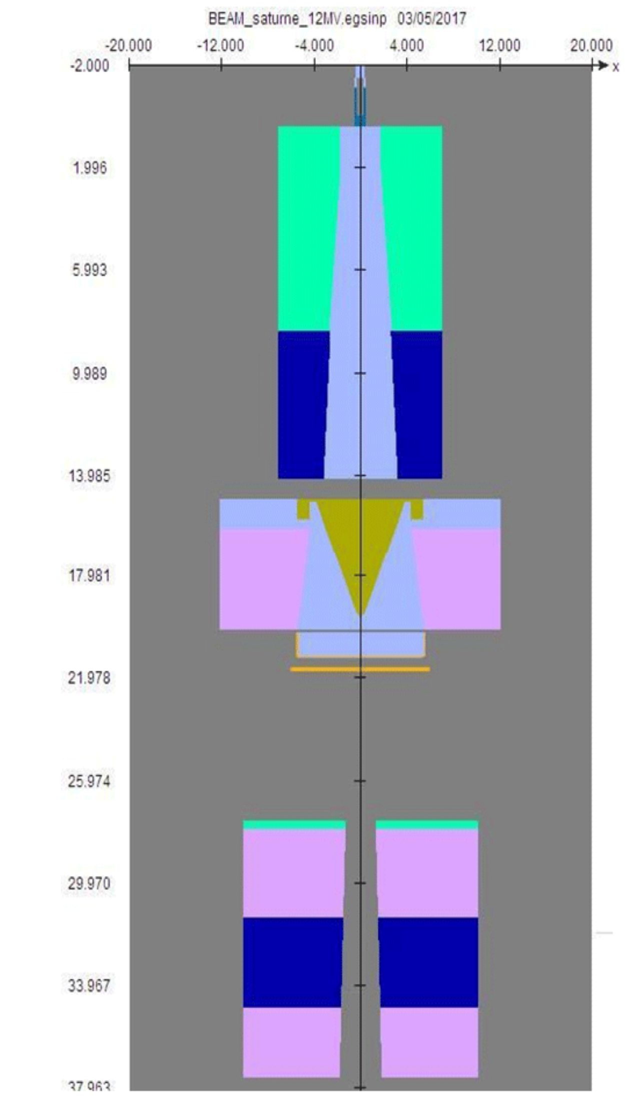

Figure 1: The two dimensional of the head Saturne 43 modeling by BEAMnrc

The PSF obtained at the scoring plane below the jaws depend on many different parameters used in the simulation process. The most important of them are the properties of the initial electron beam and the configuration of the accelerator components. A necessary step in the beam simulation was to make the accelerator head modeling be consistent with experimental PDD and DP curves. The experimental dosimetric data are carried out in NHLB in France [12].

We have used the tool BEAMDP (BEAM Data Processor) for analyzing the PSF obtained in the simulation. BEAMDP is an interactive program, developed for the OMEGA project. The spectral distribution, angular distribution and energy fluence from the PSF was obtained using this tool and graphs were plotted with the 2D graph plotting software QT - GRA CE.

Simulations using the BEAMnrc and DOSXYZnrc codes were run on a desktop core i7 CPU with 8 GHz RAM on the Ubuntu 14.04 system. The time of every simulation realized was 144 hours for every PSF obtained. Totally, we had a number of 18 PSF at all of this study.

Dose computation with DOSXYZnrc

Dose distribution was computed by DOSXYZnrc user code on a water phantom using the scored PSF obtained from the BEAMnrc located at z = 41.25 cm. The phantom geometries is divided into 80 × 80 × 80 slices in the x-axis that was in the cross plane direction, the y-axis was in plan direct ion, and the z-axis was in the beam (depth) direction. The phantom includes the air gap between the linac and the water tank as well as the PMMA wall of the tank. A 40 × 40 × 40 cm^3 water phantom was used to include enough backscatter material from the bottom and walls of the phantom. The size of the phantoms voxel (xyz), were defined depending on the required spatial resolution for model commissioning. The voxel dimension were 5 × 5 × 5 mm^3 for both depth and profile calculation.

The PDDs are normalized to the depth 10 cm (the ratio of dose at a depth in phantom to the value of dose at 10 cm depth) and beam profiles are normalized at 10 cm deep on the central axis [13].

The beam quality index Q which specified by $TPR_{20/10}$ [13], was calculated as the ratio of absorbed dose to water on the beam axis at the depths of 20 cm and 10 cm in a water phantom by the equation below:

$$TPR_{20,10} = 1.2661 * PDD_{20,10} - 0.0595$$

The gamma-index method was used to quantitatively compare the DOSXYZnrc dose distributions with measured dose distributions data [14,15]. Computations were assessed with respect to a gamma index of 1.5%/1mm.

Results and Discussion

The calculated data were compared to measurements. The results are summarized below. Figure 2 shows measured and calculated PDD curves for photons beams. Figure 3 show comparisons between measured and calculated DP at the depth of 10 cm. The PDDs are normalized to the depth 10 cm (the ratio of dose at a depth in phantom to the value of dose at 10 cm depth) and beam profiles are normalized at 10 cm deep on the central axis [13].

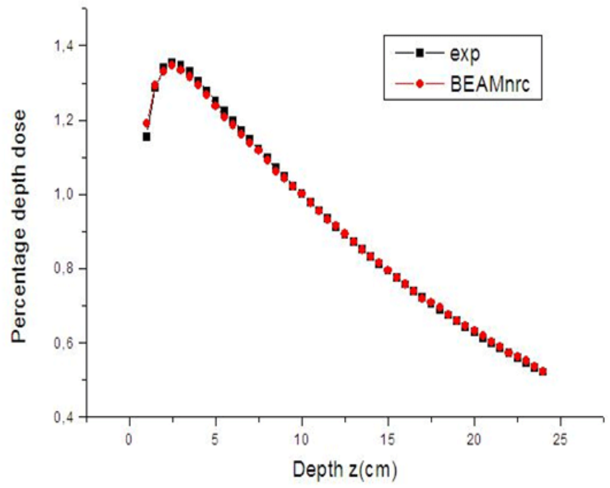

Figure 2: Comparison between BEAMnrc and experimental PDD curve in the water phantom on 10 × 10 cm^2 field size for 12 MV beam

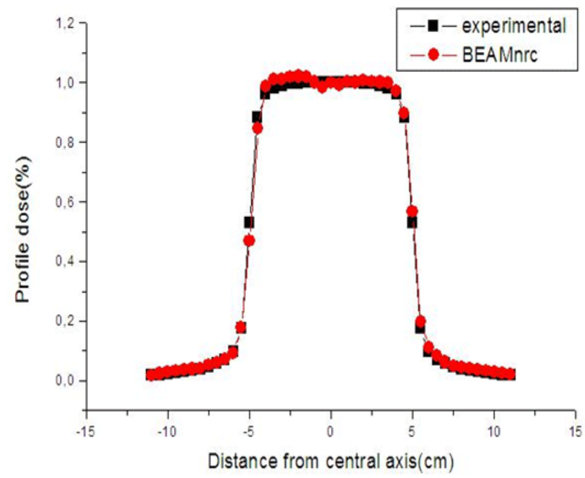

Figure 3: Comparison between BEAMnrc and experimental cross-plane profiles dose in the water phantom at 10 cm depth on 10 × 10 cm^2 field size for 12 MV beam.

The figure 4, 5 and 6 show the spectral distribution, the energy fluence distribution and angular distribution beneath a treatment head of 12 MV linac. This figures 4, 5, and 6 are obtained with BEAMDP code that analyze the data in the PSF located at z= 41.25 cm below the jaws component.

The present work shows that changing the initial electron source properties electron beam energies and FWHM, we can derive the best match value for the energy of 11.8 MeV and the FWHM = 0.07 cm which 93.6% (PDD) and 77.8% (DP) of the calculated data points agree with experimental data within 1.5%/1mm using the gamma index method, see the table I and table II below:

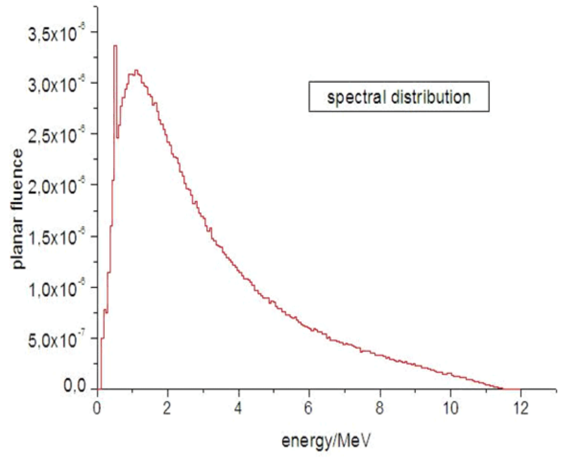

Figure 4: Spectral distribution beneath treatment head of a Saturne 12 MV.

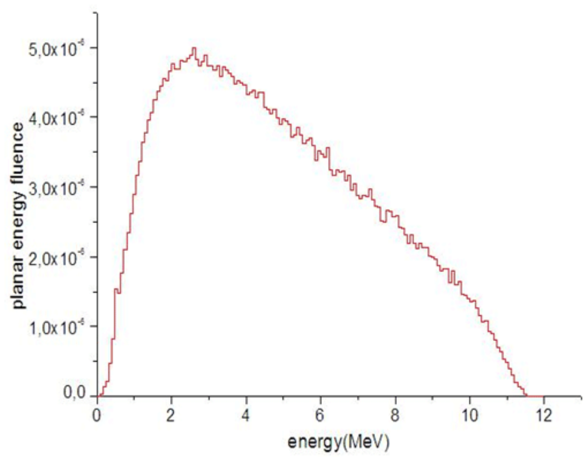

Figure 5: Energy fluence distribution beneath treatment head of a Saturne 12 MV.

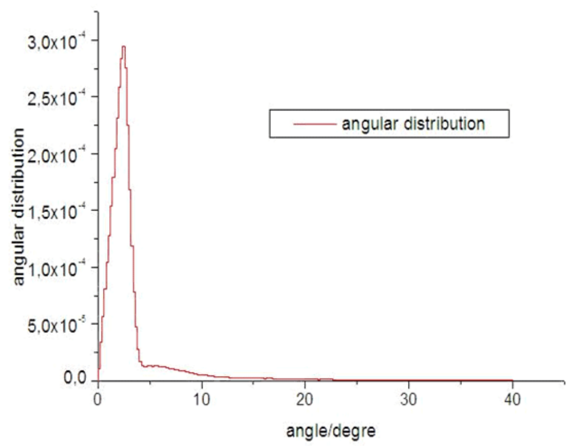

Figure 6: Angular distribution beneath treatment head of a Saturne 12 MV.

Table I: The gamma index results for PDD and Off-Axis DP with initial electron beam energies changed from 11.4 MeV to 12.2 MeV.

Initial properties		Gamma index <1.5%			
Energy (MeV)	**FWHM (cm)**	**PDD (%)**	**Dose Profile (%)**	**$PDD_{20,10}$**	**Dmax**
11.4	0.17	93.6	64.4	0.622	2.5
11.5	0.17	93.6	66.7	0.623	2.5
11.6	0.17	85.1	75.6	0.6198	2.5
11.7	0.17	91.5	62.2	0.6381	2.5
11.8	0.17	91.5	68.9	0.6265	2.5
11.9	0.17	93.6	66.7	0.6192	2.5
12	0.17	93.6	64.4	0.6211	3
12.1	0.17	91.5	75.6	0.6287	3
12.2	0.17	93.6	64.4	0.6292	3

Table II: The gamma index results for PDD and off-Axis DP with FWHM altered from 0.03 cm to 0.19 cm.

Initial properties		Gamma index <1.5%	
Energy (MeV)	**FWHM (cm)**	**PDD (%)**	**Dose Profile (%)**
11.8	0.19	91.5	71.3
11.8	0.17	93.6	68.9
11.8	0.15	85.1	60
11.8	0.13	91.5	64.4
11.8	0.11	91.5	73.3
11.8	0.09	93.6	60
11.8	0.07	93.6	77.8
11.8	0.05	91.5	68.9
11.8	0.03	93.6	64.4

The beam quality index Q which specified by $TPR_{20/10}$ [13], defined as the ratio of absorbed dose to water on the beam axis at the depths of 20 cm and 10 cm in a water phantom. $TPR_{20,10}$ is a measure of the effective attenuation coefficient, and describes the approximately exponential decrease of a photon depth-dose curve

$$TPR_{20,10} = 1.2661 * PDD_{20,10} - 0.0595$$

We compared our results with some previous study from the literatures for The beam quality index TPR20/10 and the mean energy Emoy which agree better in comparison with our work, as J El Bakkali, [11] with the code GEANT4 2014, BLAZY, [12] with the code PENELOPE 2007, and BOUCHRA [17] with the code PENFAST 2009, see the below table III:

Table III: Comparison between EMOY and $TPR_{20/10}$

	Experiment	BEAMnrc	[12]	[11]	[17]
E_{moy}	-	3.26	3.24	3.34	3.23
$PDD_{20,10}$	0.628	0.627	0.627	0.628	0.626
$TPR_{20,10}$	0.73	0.73	0.73	0.73	0.73

Conclusion

Monte Carlo simulation of the treatment head of the Saturne 43 machine was successfully done using BEAMnrc code. The PSF obtained in the simulation with BEAMnrc code was used as an input source with the DOSXYZnrc user code that may be using for other dosemetric studies. The dosemetric parameters that we obtained in the simulation studies such as PDD and DP was in good agreement with the experimental measurements and the $TPR_{20/10}$ was well matching with the published values with others MC codes. That shows the efficacy and accuracy of the method of changing the initial properties of electron source to obtain the discrepancies results within 1.5%/1 mm in this present paper.

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