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Modeling of a Linear Accelerator Saturne 43 and Study of Photon Dose Distributions

A.ZEGHARI*, R.SAAIDI, M.MGHAR, R. CHERKAOUI EL MOURSLY

Laboratory of Nuclear Physics, Faculty of Sciences, , Mohammed V University,
Rabat, Morocco
krmzeghari@gmail.com

***Abstract*— BEAMnrc is a widely used Monte Carlo (MC) code for simulation of photon and electron transport in the radiotherapy area. The aim of this study was to ameliorate a technique that changing the initial properties of incident electron beam as purpose to have the difference between calculated and measured values of doses produced by the linear accelerator (linac) Saturne 43 machine to be within 1.5%/1mm. We changed the initial electron energy and full width half maximum (FWHM) of the radius of the electron beam incident on the tungsten target to find the percentage depth dose(PDD), dose profile(DP) curves, the tissue-phantom ratio $TPR_{20/10}$, the energy fluence distribution and angular distribution for a square field size 10×10 cm^2. The value of $TPR_{20/10}$ agrees well with the publisher related works, also we could find quantitatively good results which agree well with experimental PDD and lateral profiles at 10 cm depth. Moreover, we could reduce the discrepancy between measured and calculated data photon dose distributions to be within 1.5%/1mm in the gamma index method for the energy 11.8 MeV and FWHM= 0.07 cm. Using BEAMnrc code on modeling and simulation of the treatment head of the Saturne 43 machine was successfully done altering the initial properties of electron source. That shows the efficacy and accuracy of the technique used in this paper to obtain the discrepancy within 1.5%/1 mm.**

***Keywords*— Monte Carlo; photon dose distribution; BEAMnrc; Tissue-Phantom Ratio**

I. 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. External beam radiation is delivered by aiming high-energy rays (photons) to the position of the tumour to destroy cancer cells. 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 tumour, 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.

Monte Carlo techniques are the reference tool for precise dose calculations and their accuracy has been fully quantified in the literature. 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.

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 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 multi levelled equations, graphics, and tables are not prescribed, initial electron beam parameters for radiotherapy photon beams. Verhaegen and Seuntjens [1] used the mean energy of 6 MeV and the FWHM electron spot of 0.2 cm. Sheikh-Baghri and Rogers [2] 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

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0.01 to 0.19 cm. Tzedakis and al. [3] 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 and al [4] 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 [5] for the Siemens ONCOR machine more precisely studied the source parameters based on additional measurements of non standard characteristics. Mohammad Taghi Bahreyni Toossi and al [6] used the mean energy of 6 MeV and the FWHM electron spot of 0.2 cm. Recently, J. Bakkali et al [7] 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.

II. MATERIALS AND METHODS.

A. *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 plane below the jaws where photons were written to a phase space file (PSF). The PSF was used as a source on the DOSXYZnrc user code in the second step, where particle were transported through a $40\times40\times25$ cm^3 water phantom.

B. *Modelling of the head geometry With BEAMnrc*

The head of the Saturne 43 linac, used at CEA list LNHB for 12 MV photon mode has a titanium window, target of tungsten used to generate photon primarily from bremsstrahlung interactions between the accelerated electron and the target, primary collimator of composite material WNiCu (W, Ni, Cu) and XC 10 (C, Mn, Fe) to limit the dose to the maximum usable field size, flattening filter of stainless steel used to generate a beam of uniform intensity, secondary collimator of Pb, monitor unit chamber of Kapton, aluminum plaque and finally X and Y jaws that are composite from mixture WNiCu, XC 10 and Pb. Figure 1 shows a schematic of the Saturne 43 head that we modelled with BEAMnrc code.

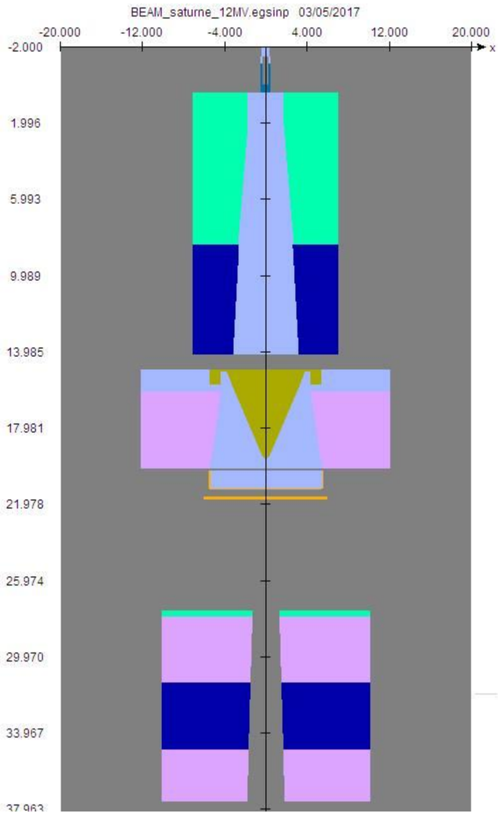

Fig. 1 The two dimensional of the head Saturne 43 modelling by BEAMnrc

BEAMnrc code was used to model the detailed geometry of the treatment head according to the manufacturer's data. We use the Source number, ISOURC=19 with Gaussian distribution in the x

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and y plane with origin on beam axis from FWHM=0.03 cm to FWHM=0.19 cm by step 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].

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 (LNHB) PDD and DP curves [10]. PDD and DP were measured experimentally in a 30 × 30 × 30 cm3 water tank. For a 12 MV photon beam, the entrance surface of the tank was positioned at 90 cm from the source and an irradiation field of 10 × 10 cm² was defined 100 cm from the source. The PDD and DP (at the 10 cm reference depth) were measured using a PTW-31002 cylindrical IC (sensitive volume of 0.125 cm 3).

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 2 D graph plotting software QT-GRACE.

Simulations using the BEAMnrc and DOSXYZnrc codes were run on a desktop core i7 CPU with 8 GHz RAM on Ubuntu 14.04 system for 144 hours for every PSF. Finally we have 18 PSF used in this study.

C. 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 80×80×50 slices in the x-axis that was in the cross plane direction, the y-axis was in plan direction 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 $40\times40\times25$ cm^3 water phantom was used to include enough backscatter material from the bottom and walls of the phantom. The size of the phantom's voxel (xyz), were defined depending on the required spatial resolution for model commissioning. The voxel dimension were $5\times5\times5$ mm^3 for both depth and profile calculation.

The water phantom was placed at 90 cm from the tungsten target and the square field size 10×10 cm^2 was considered at 100 cm, IAEA2000 **[8]**.

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

III. Results and discussion

The calculated data were compared to measurements. The results are summarized below. Fig.2 show measured and calculated PDD curves for photons beams. Figures 3 show comparisons between measured and calculated DP at the depth of 10 cm. The PDDs are normalized to the depth 10cm (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 [8].

The fig. 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.

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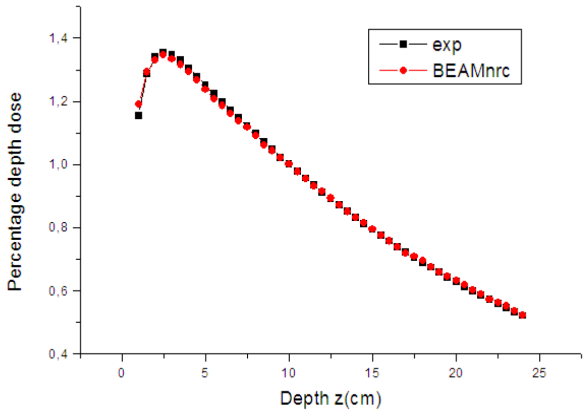

Fig. 2 PDD curve in the water phantom for 10×10 cm^2 field size for 12 MV beam

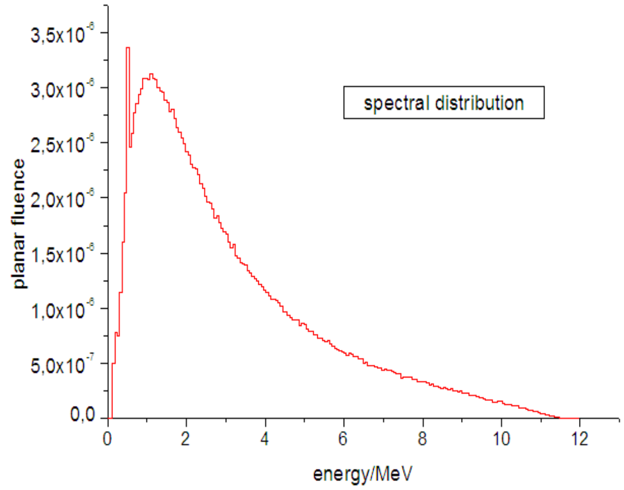

Fig. 4 Spectral distribution beneath treatment head of a Saturne 12 MV .

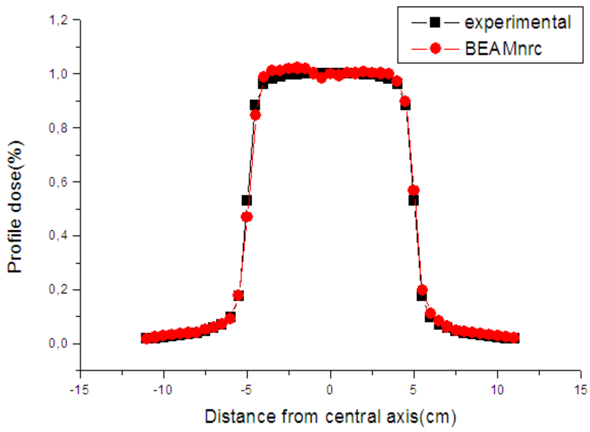

Fig. 3 Cross-plane profiles dose in the water phantom at 10 cm depth for 10×10 cm^2 field size for 12 MV beam

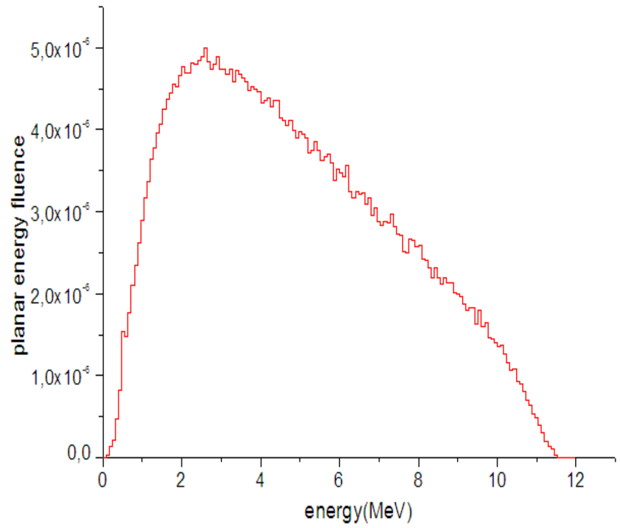

Fig. 5 Energy fluence distribution beneath treatment head of a Saturne 12 MV

The validation of the MC calculation results with experimental data was done for the open fields 10×10 cm^2 comparing the obtained PDD and off-axis DP. The differences between experimental and MC PDD results in the build-up region were more significant and especially at the surface. Possible for reason of contaminating neutrons, scattered electrons from the phantom and other parameters could be responsible for this mismatch. Regarding the off-axis DP there was a good agreement

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between measurements and calculations. A slight difference was seen in the penumbra region. These discrepancies are due to the nature of the penumbra region of the beam.

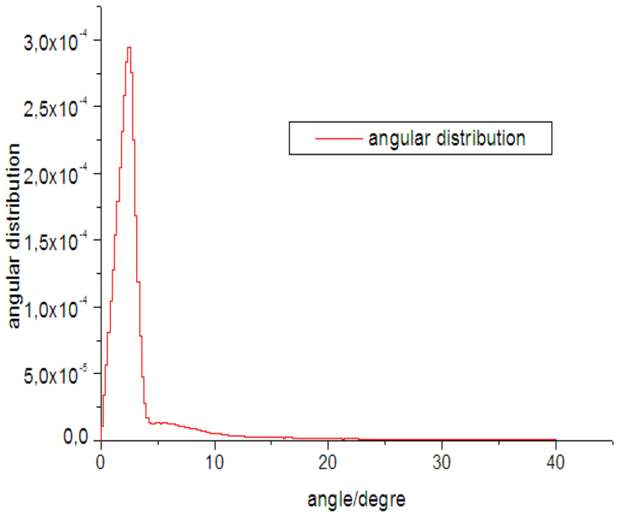

Fig. 6 Angular distribution beneath treatment head of a Saturne 12 MV.

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, see the table I and table II below:

TABLE I
THE GAMMA INDEX'S 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 (%)**	**$D_{20/D10}$**	**D_{max}**
11.4	0.17	93.6	64.4	0.6220	2.5
11.5	0.17	93.6	66.7	0.6230	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 III
THE GAMMA INDEX'S 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 $TPR_{20/10}$ [8], 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.

$$TPR20, 10 = 1.2661*PDD20, 10 - 0.0595$$

We compared our results with some previous study from the literatures which agree better with our work, as J. El Bakkali **[7]** with the code GEANT4 2014, BOUCHRA **[11]** with the code PENFAST 2009, BLAZY [10] with the code PENELOPE 2007, see the table III:

TABLE III
COMPARISON BETWEEN E_{MOY} AND $TPR_{20/10}$

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	Experiment	**Beamnrc**	**[10]**	**[7]**	**[11]**
E_{moy} (MeV)	-	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

IV. 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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