Photon beam quality study with thickness of air gap under Linac head based on maximum fluence rate investigation at the beam edge

Mohamed BENCHEIKH*, Abdelmajid MAGHNOUJ, Jaouad TAJMOUATI, Abdesslam LAMRABET and Abdessamad DIDI

LISTA Laboratory, Physics Department, Faculty of Sciences Dhar El-Mahraz, University of Sidi Mohamed Ben Abdellah, Fez, Morocco
*Corresponding e-mail address: bc.mohamed@gmail.com

Abstract

Air gap under Linac head is the last material in photon beam path before reaching patient's skin. The air atoms interact with photons and affect the beam quality in radiotherapy treatment. How photon beam varies at the beam edge when photons are traveling from gantry to patient traversing the air gap? The purpose of this work is to analyze the photon fluence at the beam edge with air gap thickness and to assess how air gap above patient can alter the photon beam quality at the beam edge. The Monte Carlo Linac head model was performed for 6 MV photon beam produced by Varian Clinac 2100.
The photon beam fluence decreased in depth with air gap under Linac head. At the beam edge, the primary photons interact with air atoms in addition to scattered photons coming from the inner surface of jaws that are of low energy contaminated the photon beam before reaching patient's skin. For predicting the maximum photon fluence rate with slab thickness of the air gap, a mathematical sigmoid law is established to describe how maximum photons fluence rate can vary with thickness and to enable us to know the photon beam quality variation according to air gap thickness.

Keywords: Material filtration, Monte Carlo simulation, Photon beam softening, Air gap study, BEAMnrc.

I. Introduction

The delivery of high tumor dose is the goal of radiation therapy while minimizing dose to healthy tissue [1]. Increasing the air gap was found to reduce the dose beyond the secondary buildup region [2]. The air gap is natural material inside radiotherapy department and is an integral part in photons beam path when patient is treated by radiation. The technology evolution of Linac considering the air effects on delivered dose based on quality management protocols that govern the verification and calibration of Linac head by establishing the facility rules [3-5]. International Commission on Radiation Units and Measurements recommends that the absorbed dose to the radiation therapy target volume should be delivered to an accuracy of 5% or better [6]. In this context, we have studied the air gap effects on photon beam fluence at the beam edge for checking the dosimetry quality with air gap thickness.

The radiotherapy quality aims to increases the killing of tumor cells and improve the patient's life quality by reducing the time treatment. The photon beam produced should conserve its power when traveling from target to patient. However, the air gap thickness is almost 60 cm. In this works, the air gap effects on beam quality are investigated in term of photon beam fluence with air gap thickness for evaluating the air impacts on delivered dose before reaching the patient's skin because the air above the patient is the last material slab and it can alter the beam quality and especially at the beam edge.

Monte Carlo calculations are essential methods in radiation therapy study. To take full advantage of this tool, the Linac head has to be simulated in detail and the initial beam parameters have to be known accurately. The modeling of the beam opens various areas where Monte Carlo calculations prove extremely helpful, such as for Linac head design and commissioning of a therapy facility as well as for quality assurance verification and radiotherapy quality improvement [7-9]. One of the major reasons to make this Monte Carlo study that it allows modelling the Linac head and calculating photon fluence properties at the beam edge.

For radiotherapy quality improvement, we have previously studied the beam quality improvements by studying beam softening as main parameter for examining the flattening filter materials [10,11] and also by studying the flattening filter volume reduction impacts on delivered dose [12,13]. The dosimetry quality is investigated for flattening filter free of Linac configuration [14, 15]. In this study, the beam quality is studied at the beam edge for radiotherapy quality and radioprotection facility and we have proceed to introduce a mathematical law for predicting photon beam fluence variation with air gap thickness and also with off-axis distance.

In this work, Monte Carlo geometry is building for 6 MV photon beam Varian Clinac 2100 by BEAMnrc [16], the Linac head model is representing as realistically as possible. Thereafter, Monte Carlo simulation is validated. The photon fluence is determined with off-axis distance for each air gap slab thickness of 7.5 cm. The nominal photon beam energy is 6 MV, the field size is 10×10 cm^2 and the source-to-surface distance (SSD) is 100 cm. The physical process simulation is based on EGSnrc code where the transport of radiation is simulated as realistically as possible [17].

II. Materials and methods:

1. Monte Carlo simulation:

Monte Carlo simulation of Linac head provides both accurate and detailed energetic and dosimetric calculation in radiotherapy physics [18]. In this study, Linac head was modeled by BEAMnrc and then phase space files (PSF) were generated. PSF were used to determinate particles' properties and their characterizations using BEAMDP code [19].
Figure 1 shows head components, including target, primary collimator, flattening filter, ion chamber, and secondary collimator (jaws) were simulated based on manufacturer-provided information (Varian Medical System) by BEAMnrc code.

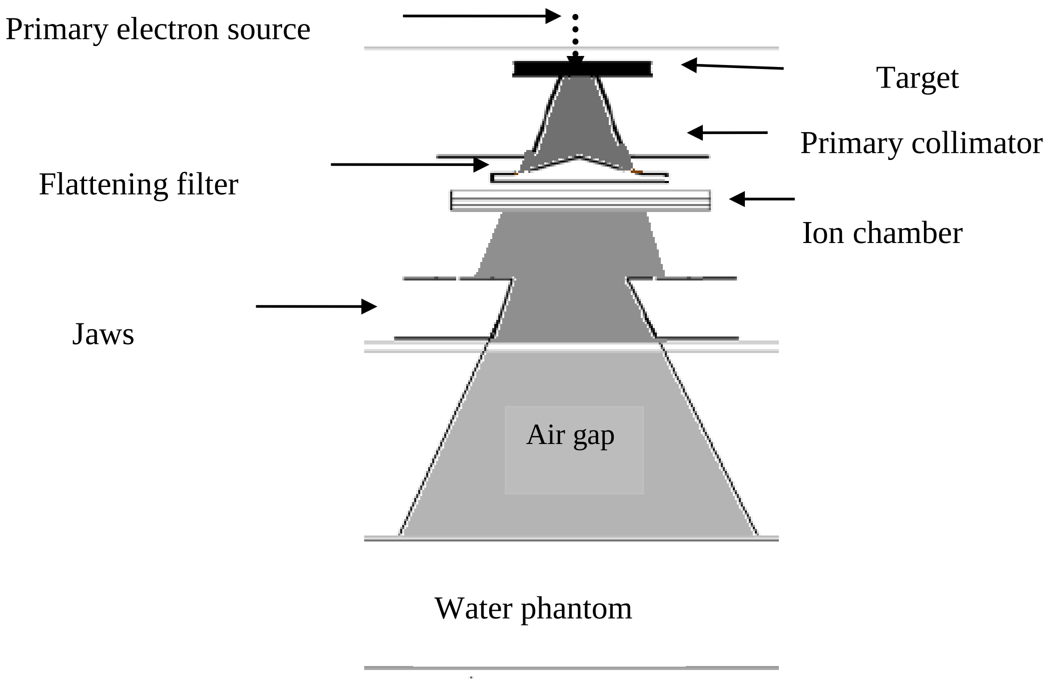

Figure 1: Cross section view of Monte Carlo geometry of Linac head and photons path from target to water phantom.

The histories number used in BEAMnrc is 2×10^7 with directional bremsstrahlung splitting (DBS) as variance reduction technique and it was 1000. This number is sufficient to generate a simulation statistical uncertainty of 1% and it is as determined in previous study [20].

2. Monte Carlo simulation validation

The Monte Carlo simulation of Linac head was validated with accuracy by 99% for PDD and by 98% for beam dose profile which are within the tolerance limit recommended by IAEA in TRS430 [21] and in IAEA-TECDOC-1583 [22]. This work is a subject of one of our previous scientific publications [23]. This Monte Carlo simulation was more accurate in comparison with previous study [24].

3. Sigmoid law for maximum fluence rate prediction

We have established a mathematical law for predicting maximum photon fluence rate variation at the beam edge (symmetrical sigmoid). The sigmoid formulas are established generally to govern the growth variation of biological or physical process [25].

The symmetrical sigmoidal is mathematical form which describes the variation based on exponential form. The formula 1 gives the form of the symmetrical sigmoidal:

$$f(x) = d + \frac{a-d}{1+\left(\frac{x}{c}\right)^b} \quad (1)$$

Where a, b, c and d are the constants to determine.

This mathematical form allows us to know the photon fluence variation at the beam edge for improving radiotherapy efficiency and for radioprotection reasons regarding to the operating radiation source staff and patients.

III. Results and discussion:

The air gap impacts on photon fluence are evaluated with off-axis distance and with air gap thickness. Figure 2 shows photon fluence profiles as a function of off-axis distance for each air gap slab of a thickness from 0 to 60 cm by increment of 7.5 cm.

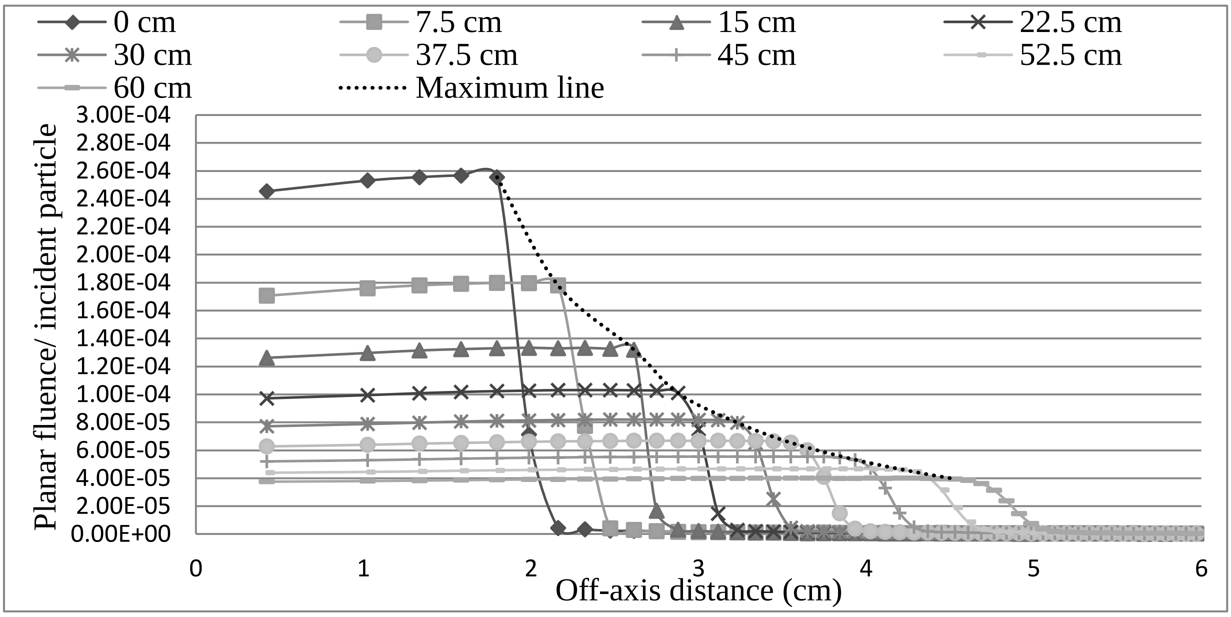

Figure 2: Photon fluence profiles as a function of off-axis distance for each sub air gap slab

It is clear from Figure 2 that the air gap affects the photon fluence that decrease with air gap thickness. Photon fluence increased with off-axis distance on flat region of the profile curves. Near the beam edge, these fluencies fall to zero but at different off-axis distance which vary with air gap thickness and they have the maximum at this point (Figure 2).

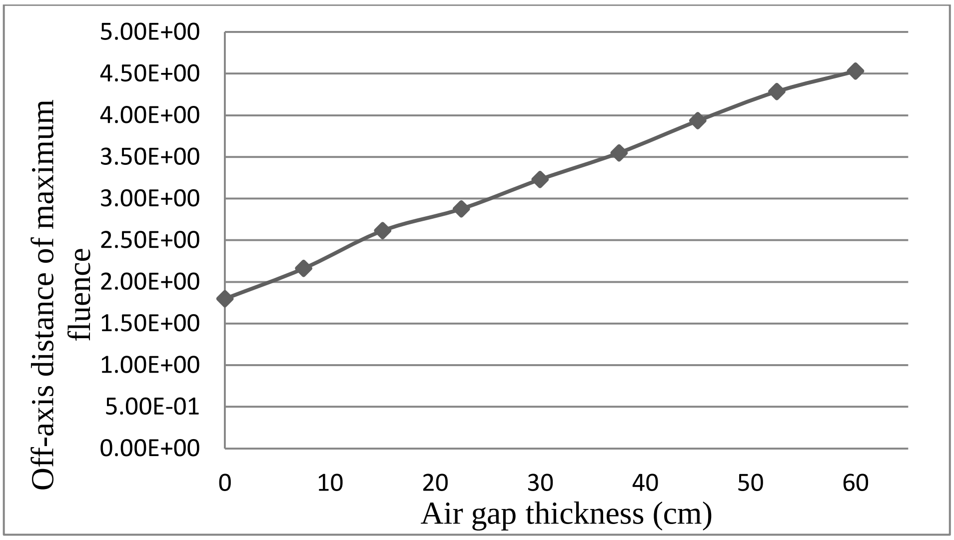

Figure 3: Off-axis distance of photon fluence maximum variation as a function of air gap thickness

From Figure 3, the off-axis distance of maximum fluence varies linearly with air gap thickness. This finding is natural due to inner surface of jaws that is flat. However, the question can be put in this context, how these maximums vary with off-axis distance that varies linearly with air gap thickness?

For responding to this question, we have determined the photon fluence rate at beam edge of each sub air gap thickness. The photon fluence rate is determined as a ratio of photon fluence to air gap thickness. Figure 4 gives the maximum photon fluence rate variation with air gap thickness.

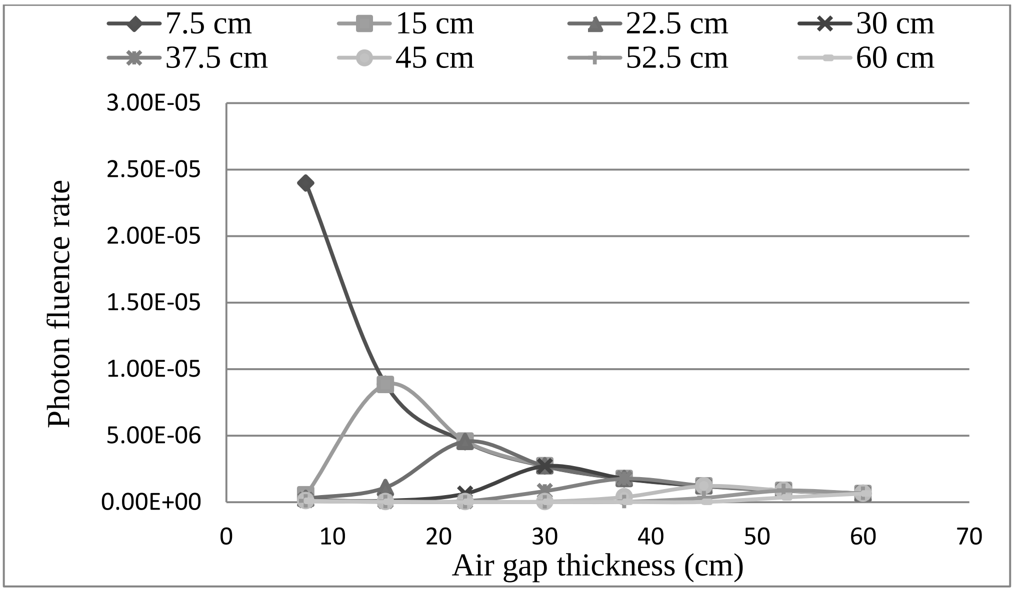

Figure 4: Photon fluence rate variation as a function of air gap thickness.

It can be seen from Figure 4 that the maximum fluence rate decreases with air gap thickness. The more significant result is that the maximum of photon fluence rate of thicker air gap overlaps with fluence rate of thinner air gap and all maximums of photon fluence rate are on maximum fluence rate curve of air gap thickness of 7.5 cm (Figure 4).

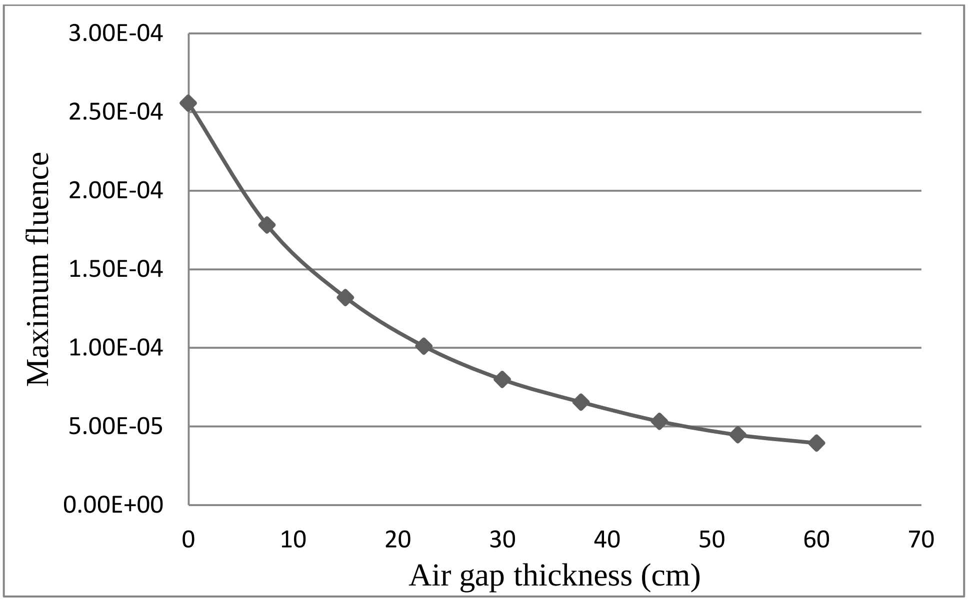

Figure 5: Photon fluence variation as a function of air gap thickness at each sub air gap slab.

Figure 5 shows the variation of maximum photon fluence with air gap thickness presented in Figure 2.

The finding in Figure 5 is natural due to photons attenuation in depth with air gap thickness. Based on this parameter and the photons attenuation, the radiotherapy quality at the beam edge is checked by the determination of the maximum fluence rate.

Figure 6 shows the maximum photon fluence rate variation with air gap thickness.

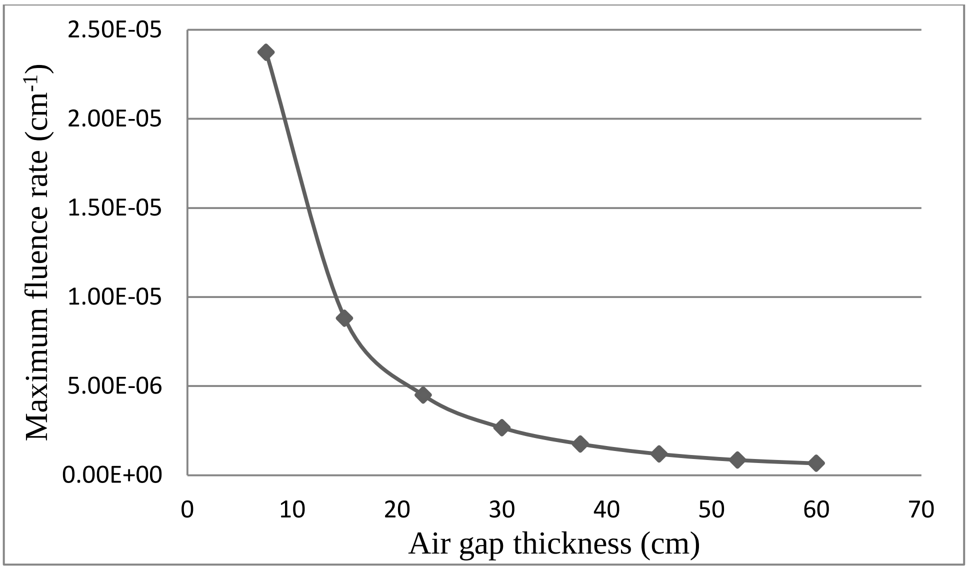

Figure 6: Photon fluence variation rate as a function of air gap thickness at each sub air gap slab.

It can be seen from Figure 6 that the maximum fluence rate decreases deeply with air gap thickness at the beam edge. So, the radiotherapy quality is strongly deteriorated with air gap thickness because the photon fluence decreases in depth. At patient's skin the photon number will decrease by 80% and in parallel, the particles contamination (electrons, low energy photons …) will increase due to the photons interaction with air atoms.

For quantifying the maximum fluence rate and subsequently the radiotherapy quality with air gap under Linac head, we have proceeded to establish a symmetrical sigmoidal law for predicting the variation maximum of photon fluence rate. The formula 2 gives the mathematical law (symmetrical sigmoidal) to assess the maximum fluence with air gap thickness.

$$\emptyset(t) = -2.64\ 10^{-7} + \frac{7.79\ 10^{-5} + 2.64\ 10^{-7}}{1 + (\frac{t}{4.71})^{1.75}} \quad (3)$$

Where *t* is the air gap thickness

Figure 7 gives the symmetrical sigmoidal law variation of maximum photon fluence rate and the associated error as a function of air gap thickness.

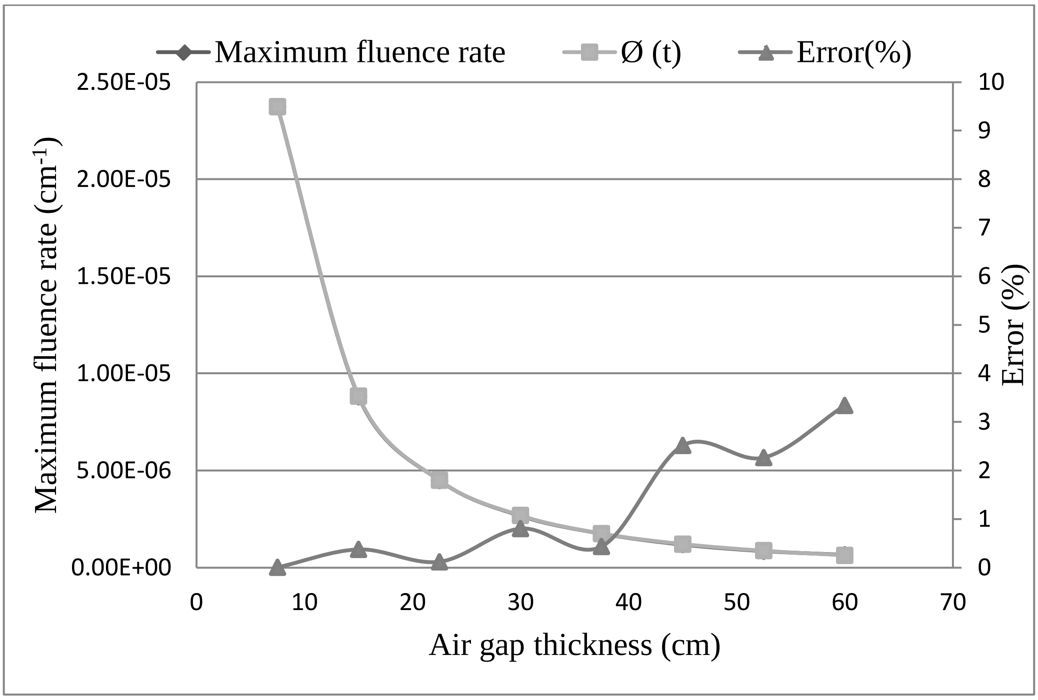

Figure 7: Maximum fluence rate variation as a function of off-axis distance (left) and the error as a function of off-axis air gap thickness (right).

It can be seen from Figure 7 that the maximum fluence rate varies as a symmetrical sigmoidal law with air gap thickness. At the beam edge, this mathematical law can reproduce the maximum fluence rate variation as a function of air gap thickness with an error under to 4% (Figure 7).

IV. Conclusion

At the beam edge, the photon beam quality is studied and investigated with air gap thickness for irradiation field size of 10×10 cm^2. The radiotherapy quality is depending on photons number distribution inside the radiation field size. The air gap under Linac head decreased strongly the photons fluence; therefore, the dosimetry quality will be deteriorated by decreasing the delivered dose in addition to particles contamination number which increased. So, the radiotherapy quality will be deteriorated at the patient's skin.

To predict theses alterations, we have established a mathematical sigmoid law to describe how photon quality is altered by air gap under Linac head. This sigmoid law allows us to know and to predict the maximum fluence rate variation at the beam edge with off-axis distance and with air gap thickness with an error under to 4%. Our study about the beam quality is a part of many studies were done about the beam quality in radiotherapy treatment [26, 27]. In perspective, we will evaluate quantitatively these impacts in term of how much air gap will reduce the delivered dose in radiotherapy treatment.

Acknowledgement

The authors would like to thank Varian Medical Systems to provide us the Varian Clinac 2100 geometry data and give us this opportunity to study the Varian linear accelerator technology and to participate in its future development.

References

[1]. H. Paganetti, H. Jiang, S.-Y. Lee, and H. M. Kooy, (2004), Accurate Monte Carlo simulations for nozzle design, commissioning and quality assurance for a proton radiation therapy facility, Med. Phys., Vol 31, N° 7, pp 2107-2118

[2]. A. Gray, L. D. Oliver, and P. N. Johnston, (2009), The accuracy of the pencil beam convolution and anisotropic analytical algorithms in predicting the dose effects due to attenuation from immobilization devices and large air gaps, Med. Phys., Vol 36 N° 7, pp 3181 -3191

[3]. D. Georg,G. Kragl, S. af Wetterstedt, P. McCavana, B. McClean, T. and Knöös, (2010), “Photon beam quality variations of a flattening filter free linear accelerator,” Med. Phys. 37, pp : 49–53

[4]. K. E. Rosser, B. Owen, A. R. DuSautoy, D. H. Pritchard, I. Stoker, and C. J. Brend, (1994), “The NPL absorbed dose to water calibration service for high energy photons,’’ IAEA-SM-330/35, Proceedings of Symposium on Measurement Assurance in Dosimetry (IAEA, Vienna), pp : 73–81

[5]. C. K. Ross, K. R. Shortt, D. W. O. Rogers, and F. Delaunay, (1994), “A test of 〖TPR〗_10^20 as a beam quality specifier for high-energy photon beams,” IAEA-SM-330/10, Proceedings of Symposium on Measurement Assurance in Dosimetry (IAEA, Vienna), pp. 309–321

[6]. ICRU Report No. 24, (1976), Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy,” International Commission on Radiation Units and Measurements (ICRU), Bethesda, Maryland.

[7]. N. Reynaert et al, (2007). “Monte Carlo treatment planning for photon and electron beams,” Rad. Phys. Chem. 76, pp : 643–686

[8]. Bencheikh M., Maghnouj A. and Tajmouati J., (2017), Energetic Properties’ Investigation of Removing Flattening Filter at Phantom Surface: Monte Carlo Study using BEAMnrc Code, DOSXYZnrc Code and BEAMDP Code, PEPAN Letters, Vol. 14 No 6, pp 921–930.

[9]. Didi A., Dadouch A., Bencheikh M., Jai O., (2017), Monte Carlo simulation of thermal neutron flux of americium–beryllium source used in neutron activation analysis , Moscow University Physics Bulletin Vol. 72 No 5 , pp : 460–464

[10]. Bencheikh M., Maghnouj A. and Tajmouati J., (2017), Photon beam softening coefficients evaluation for a 6 MeV photon beam for an aluminum slab: Monte Carlo study using BEAMnrc code, DOSXYZnrc code and BEAMDP code, Moscow University Physics Bulletin, Vol. 72 No 3, pp 263–270.

[11]. Bencheikh M., Maghnouj A. and Tajmouati J., (2017), Photon beam softening coefficient determination with slab thickness in small filed size: Monte Carlo study, PEPAN Letters, Vol. 14 No 6, pp 931–938.

[12]. Bencheikh M., Maghnouj A. and Tajmouati J., (2017), Relative Attenuation and Beam Softening Study with Flattening Filter Volume Reduction: Monte Carlo Study, Moscow University Physics Bulletin Vol 72 No 6 pp : 647–652.

[13]. Bencheikh M., Maghnouj A. and Tajmouati J., (2017), Study of Possibility to Reduce Flattening Filter Volume for Increasing Energetic Photons for High Radiotherapy Efficiency, Moscow University Physics Bulletin Vol 72 No 6 pp : 653–657.

[14]. Bencheikh M., Maghnouj A. and Tajmouati J., (2017), Dosimetry Investigation and Evaluation for Removing Flattening Filter Configuration of Linac: Monte Carlo Study, Moscow University Physics Bulletin Vol 72 No 6 pp : 640–646.

[15]. Bencheikh M., Maghnouj A., Tajmouati J., (2017), Study of photon beam dosimetry quality for removing flattening filter Linac configuration, Annals of University of Craiova Physics AUC, vol. 27, pp 50-60

[16]. Rogers D.W.O., Walters B., and Kawrakow I., 2013, BEAMnrc Users Manual, NRCC Report, Ottawa, pp 12-254.

[17]. Rogers D.W.O., Kawrakow I., Seuntjens J.P., Walters B. and Mainegra H. E., (2013), NRC User Codes for EGSnrc, NRCC Report, Ottawa, pp 6-83.

[18]. I. J. Chetty et al, (2007), "Report of the AAPM Task Group no 105: Issues associated with clinical implementation of Monte Carlo based photon and electron external beam treatment planning," Med. Phys. 34, pp : 4818–4853.

[19]. Ma C.M. and Rogers D.W.O., (2013), BEAMDP Users Manual, National Research Council of Canada, NRCC Report, Ottawa, pp 3-24.

[20]. Aljamal M. and Zakaria A., (2013), Monte Carlo Modeling of a Siemens Primus 6 MeV Photon Beam Linear Accelerator, Australian Journal of Basic and Applied Sciences, 7(10), pp 340-346.

[21]. Technical Reports Series No.430, (2004), Commissioning and Quality Assurance of Computerized Planning Systems for Radiation Treatment of Cancer, International Atomic Energy Agency, Vienna.

[22]. IAEA-TECDOC-1540, (2007), Specification and Acceptance Testing of Radiotherapy Treatment Planning Systems, International Atomic Energy Agency, Vienna.

[23]. Bencheikh M., Maghnouj A., Tajmouati J., Didi A. and Ezzati A. O., (2017), Validation of Monte Carlo simulation of linear accelerator using BEAMnrc code and DOSXYZnrc code, PEPAN Letters, Vol. 14 No 5, pp 780–787

[24]. Kadman B., Chawapun N., Ua-apisitwong S., Asakit T., Chumpu N. and Rueansri J., (2016), Consistency check of photon beam physical data after recommissioning process, Journal of Physics: Conference Series 694, 012023, IOP Publishing.

[25]. Colin P. D. Birch, (1999), A New Generalized Logistic Sigmoid Growth Equation Compared with the Richards Growth Equation, journal of Annals of Botany, Vol 83, pp 713 -723.

[26]. G. Xiong, and D. W. O. Rogers, (2008), "Relationship between %dd10x and stopping-power ratios for flattening filter free accelerators: A Monte Carlo study," Med. Phys. 35, 2104–2109

[27]. C. Ceberg, S. Johnsson, M. Lind, and T. Knöös, (2010), "Prediction of stopping-power ratios in flattening-filter free beams," Med. Phys. 37, 1164–1168