Journal of King Saud University – Science 32 (2020) 595–599

Contents lists available at ScienceDirect

Journal of King Saud University – Science

journal homepage: www.sciencedirect.com

Analysis of stabilization of photon beam softening with off-axis distance for filtration system enhancement to increase dosimetry in radiotherapy

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ARTICLE INFO

Article history:
Received 10 January 2018
Accepted 10 September 2018
Available online 11 September 2018

Keywords:
Material filtration
Monte Carlo simulation
Photon beam softening
Material study
BEAMnrc

ABSTRACT

Beam softening is depending on the material atomic number and photon beam energy for photon beam filtration; the filtration quality is essential to producing a clinical beam in external radiotherapy. Beam softening analysis is done using Monte Carlo method. The Monte Carlo model was performed for 6 MV photon beam produced by Varian Clinac 2100 with flattening filter thereafter the flattening filter was removed and replaced by slab of aluminum and copper with different thickness. The purpose of this study is to analyze the photon beam softening with off-axis distance for the reference field size of 10 × 10 cm^2; the beam softening is studied in terms of tow coefficients a_1 and a_2.

Inside the irradiation field, for aluminum slab, the coefficient a_1 varied in interval from $-1.2\ \text{cm}^{-1}$ to $1.7\ \text{cm}^{-1}$ and it has big fluctuations with off-axis distance. For copper, a_1 varied from $0\ \text{cm}^{-1}$ to $1.5\ \text{cm}^{-1}$ and it has small fluctuations with off-axis distance. The coefficient a_2, for aluminum slab, varied from $-1\ \text{cm}^{-2}$ to $0.4\ \text{cm}^{-2}$ with big fluctuations. For copper slab, a_2 varied from $-0.9\ \text{cm}^{-2}$ to $0\ \text{cm}^{-2}$ with small fluctuations. We conclude that the beam softening is very stabilized for copper than aluminum in despite of copper attenuate more photons than aluminum for same slab thickness when they are used in photon beam filtration. To increase dosimetry in radiotherapy, the flattening filter should be constructed based on low atomic number materials but with high stabilization of beam softening with off-axis distance.

1. Introduction

The knowledge of physical properties of material as beam softening is essential for improvement and development of filtration system in linac head. Monte Carlo methods have been used extensively in medical physics for modeling linear accelerators and for radiation therapy dose calculation and beam energy study (Chetty et al., 2007; Reynaert et al., 2007; Bencheikh et al., 2017a). One of the major reasons to make this Monte Carlo study that it allows modelling the linac head and calculating the photon fluence properties at water phantom surface. This study aims to analyze the stabilization of photon beam softening with off-axis distance for aluminum (Al) and copper (Cu) slab. The material slab was placed instead of flattening filter in Monte Carlo model of Varian Clinac 2100. In our previous works about photon beam softening, the beam softening is evaluated as a parameter to developing linac head in filtration system quality (Bencheikh et al., 2017b, 2017c). In this work, we study the stabilization of beam softening for improving the flattening filter based on low atomic number metals.

Many studies were done for beam softening with energies, with depths and with wedge angles (Muhammad et al., 2009; Doswell and Cunningham, 2000). In this work, photon beam softening coefficients are determined as a function of off-axis distance for both materials aluminum (Al) and copper (Cu). Monte Carlo geometry is building for 6 MV photon beam Varian Clinac 2100 by BEAMnrc (Rogers et al., 2013a), the linac head model is representing as realistically as possible. Thereafter, Monte Carlo simulation is validated and thereafter, the flattening filter is removed and replaced by aluminum (Al) and copper (Cu) slab by different thicknesses in linac head model. The slab thicknesses are 2.5 mm, 5 mm, 7.5 mm and 10 mm for both materials. 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

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Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.jksus.2018.09.006

is based on EGSnrc code where the transport of radiation is simulated as realistically as possible (Rogers et al., 2013b).

2. Materials and methods

2.1. Monte Carlo simulation

Monte Carlo simulation is a technique that provides both accurate and detailed energetic and dosimetric calculation in radiotherapy physics (Bencheikh et al., 2017a; Didi et al. 2017). Monte Carlo simulation of linac was done by BEAMnrc to generate phase space file (PSF) that contained particles' information at water phantom surface, PSF was used to determinate particles' properties and their characterizations by BEAMDP (Ma and Rogers, 2013).

Fig. 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.

The initial electron energy is not clearly provided by the manufacturer and varies among linacs of the same model (Sheikh-Bagheri and Rogers, 2002a, 2002b). Thus, electron beam energy was selected by comparing measured and calculated distribution for 10 × 10 cm^2 field size using iterative Monte Carlo simulation by varying incident electron energy above target and the physical characteristics of the source. As results, the primary electron source above the target was elliptical form and it had the Gaussian spread. Its characterizations were X and Y coordinates equal to 1.4 mm, the mean angle spread of primary electrons was 1° and the electron source energy was 6.52 MeV.

The histories number used in BEAMnrc was 2×10^7 with directional bremsstrahlung splitting (DBS) as variance reduction technique and DBS was 1000. This number was sufficient to generate a simulation statistical uncertainty of 1% and it was as determined in other previous studies (Aljamal and Zakaria, 2013).

The Monte Carlo simulation was validated with accuracy by almost 99% for PDD and by almost 98% for beam profile, these values are within tolerance limit recommended by IAEA in TRS430 (IAEA, 2004) and in IAEA-TECDOC-1583 (IAEA, 2007). This work is a subject of one of our scientific publications (Bencheikh et al., 2017d). So, this Monte Carlo simulation was more accurate in comparison with previous studies (Kadman et al., 2016). The Monte Carlo method is considered as a basic technique to investigate the beam quality in radiotherapy physic (Xiong and Rogers, 2008; Ceberg et al., 2010). In our previous study we have studied the possibility to reduce the flattening filter volume by studying the relative beam softening due to flattening filter volume reduction (Bencheikh et al., 2017e, 2017f) and keeping the photon beam quality as a high as possible.

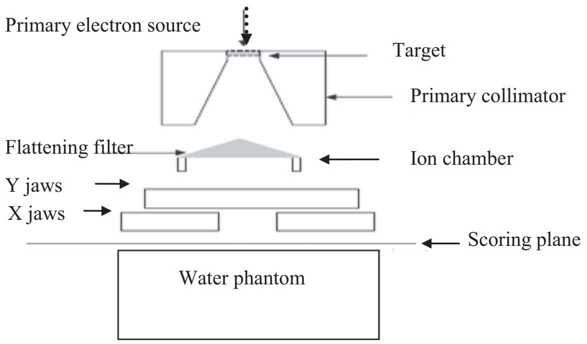

Fig. 1. Cross section view of Monte Carlo geometry of linac head and phase space file scoring plane position to water phantom.

2.2. Investigation and evaluation of beam softening

Beam softening was evaluated with slab thickness that was inserted instead of flattening filter in the validated Monte Carlo model of linac head with different thicknesses of 2.5 mm, 5 mm, 7.5 mm and 10 mm. it is described by two coefficients a1 and a2. The quadratic equation can be used to calculate the off-axis linear attenuation coefficient μ as a function of a1 and a2 (Bencheikh et al., 2017c; Muhammad et al., 2009; Doswell and Cunningham, 2000):

$$\mu(r) = \mu(0)(1 + a_1 r + a_2 r^2) \quad (1)$$

where

r is off-axis distance, and μ*(0)* and μ*(r)* are the attenuation coefficients at the central axis and at off-axis distance *r*, respectively.

The total attenuation coefficient μ*(r)* was calculated as a function of off-axis distance *r* using the following formula:

$$\mu(r) = \frac{-\ln\left(\frac{\varnothing_0(r)}{\varnothing(r)}\right)}{SSD} \quad (2)$$

where

$\varnothing_t$ *(r)*: photon fluence for slab thickness *t* at the phantom surface,

$\varnothing_0(r)$: photon fluence removing slab at the phantom surface,

r : off-axis distance.

SSD : source-to-surface distance

The Eq. (3) was used to calculate the mass attenuation coefficient for the compound material:

$$\mu = \sum \mu_i \omega_i \quad (3)$$

where

μ_i: is mass attenuation coefficient of *i*th element in photon beam path;

ω_i: is weight fraction of *i*th element.

According to formula (3), total attenuation coefficient varied with inserted slab thickness, because the weight fraction of air and inserted slab varied with slab thickness. The photon fluence was determined based on PSF using BEAMDP code, PSF were generated by BEAMnrc code at water phantom surface.

3. Results and discussion

Fig. 2 shows photon fluence profiles as a function of off-axis distance for aluminum (Al) slab and copper (Cu) slab, they were determined at water phantom surface for four thicknesses of 2.5 mm, 5 mm, 7.5 mm and 10 mm.

Photon fluence profiles decreased with off-axis distance and slab thickness for both materials aluminum and copper. It is can be seen that photon fluence decreased more with slab thickness using copper slab compared to aluminum slab (Fig. 2). At beam edge, photon fluence had the same value for both materials aluminum and copper and approximately was at 3.7 10^{-5} photons/incident particle/cm^2 and for all slab thicknesses.

Total attenuation coefficient was also evaluated with slab thickness for both materials aluminum and copper. Fig. 3 presents the total attenuation coefficient variation as a function of off-axis distance for aluminum and copper and it was determined according to formula (2).

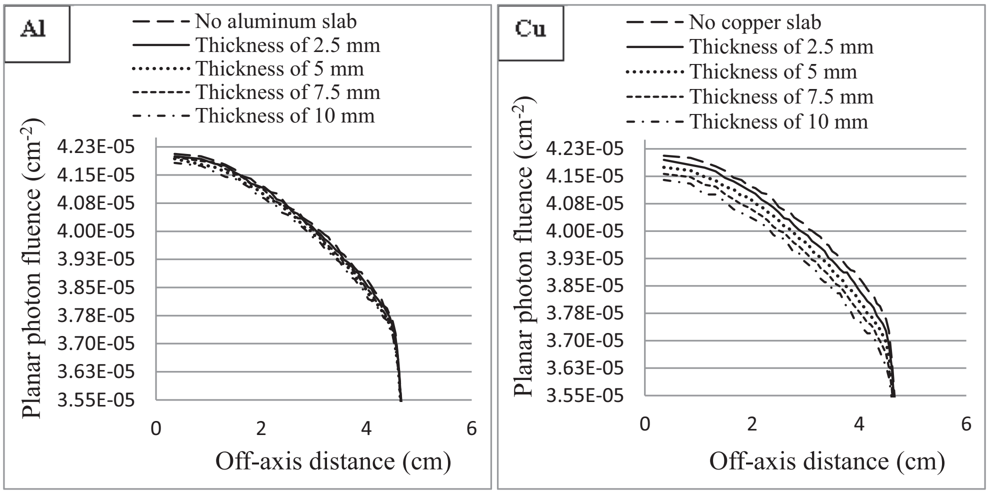

Fig. 2. Photon fluence profiles with slab thickness as a function of off-axis distance.

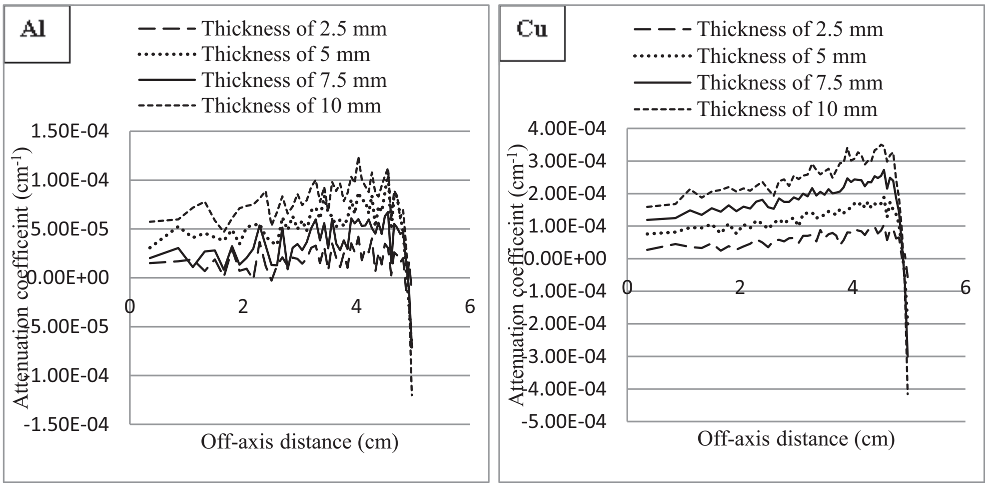

Fig. 3. Attenuation coefficient $\mu(r)$ with slab thickness as a function of off-axis distance.

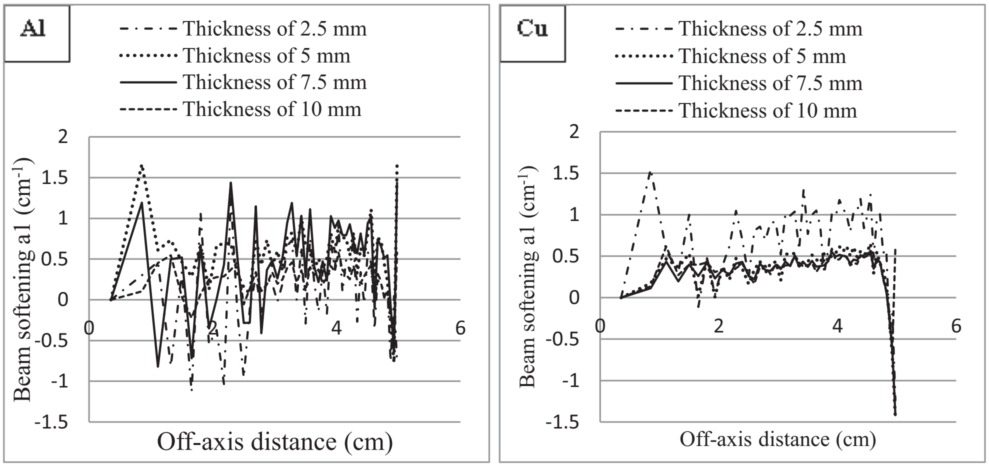

Fig. 4. Photon beam softening coefficients a_1 with slab thickness a function of off-axis distance.

From Fig. 3, attenuation coefficients increased with slab thickness for both materials aluminum and copper. Total attenuation coefficient was high for copper in comparison to aluminum slab. Attenuation coefficient increased also with off-axis distance that means that beam softening coefficients could vary with off-axis distance.

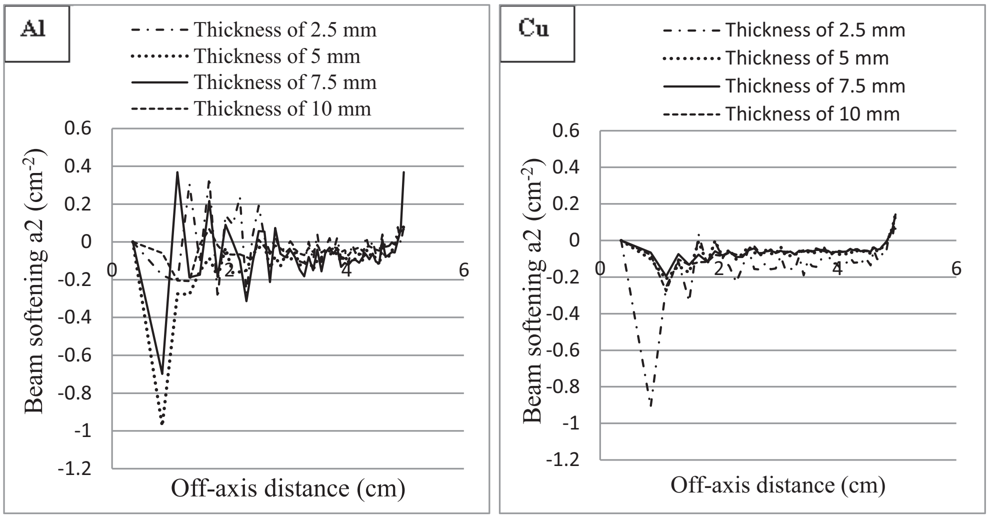

Fig. 5. Photon beam softening coefficients a_2 with slab thickness as a function of off-axis distance.

Photon beam softening was evaluated via two coefficients a_1 and a_2 and they were calculated as a function of off-axis distance according to formula (1). Figs. 4 and 5 present variation of photon beam softening coefficients a_1 and a_2 respectively with off-axis distance.

From Fig. 4, coefficient a_1 had big fluctuations with off-axis distance for aluminum slab and we can't say that a_1 was positive or negative but for copper it was smooth and had small fluctuations with off-axis distance, thereafter the sign of a_1 is positive. Inside the irradiation field, beam softening coefficient a_1 variation was in an interval from $-1.2\ \mathrm{cm}^{-1}$ to $1.7\ \mathrm{cm}^{-1}$ for aluminum slab and it was from $0\ \mathrm{cm}^{-1}$ to $1.5\ \mathrm{cm}^{-1}$ for copper slab.

It can be seen from Fig. 5 that the coefficient a_2 is as the coefficient a_1 in terms of fluctuations variation with off-axis distance for both materials. Beam softening a_2 was very high near the beam central axis and decreased with off-axis distance for both materials aluminum and copper but it was very low compared to beam softening coefficient a_1 (Figs. 4 and 5).

For aluminum slab, a_2 varied from $-1\ \mathrm{cm}^{-2}$ to $0.4\ \mathrm{cm}^{-2}$ and for copper slab, it varied from $-0.9\ \mathrm{cm}^{-2}$ to $0\ \mathrm{cm}^{-2}$. Beam softening coefficient a_2 increased with slab thickness for copper and for aluminum, beam softening of aluminum had big fluctuations with off-axis distance. So for aluminum, the coefficient softening a_2 is not stable with off-axis distance. For using aluminum as flattening filter, the beam softening should be stabilized with off-axis distance.

4. Conclusion

The beam softening is smoother and more stable for copper slab than aluminum slab, that explains the reason that copper is more useful in linac head design and especially in beam modifier manufacturing. For using low atomic number material in the conception of filtration system the beam softening should be stabilized with off-axis distance and the fluctuations must be small.

Concerning beam softening, our study is in agreement with study of Muhammad M. (Muhammad et al., 2009). It is also in agreement with our previous works (Bencheikh et al., 2017b, 2017c). In this work, the stability of beam softening is studied and the reasons to use copper in linac design as a beam modifier have demonstrated. For adopting the use of low atomic metal in the filtration system manufacturing, the quality of produced beam is crucial for radiotherapy improvement (Bencheikh et al., 2017g, 2017h).

For basic studies, the beam quality should be strangely present in our future works as it was investigated before and especially in delivered dose investigation (Georg et al., 2010; Rosser et al., 1994). For best evaluation of beam softening using low atomic number metals and for further implementation of these results, many experiment studies should be done based on beam quality parameters (Seuntjens et al., 2000, Ross et al., 1994).

Acknowledgements

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.

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