ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА / NUCL. PHYS. AT. ENERGY 21 (2020) 275-280 ISSN 1818-331X

ТЕХНІКА ТА МЕТОДИ ЕКСПЕРИМЕНТУ
ENGINEERING AND METHODS OF EXPERIMENT

УДК 615.849+621.384.64 https://doi.org/10.15407/jnpae2020.03.275

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MONTE CARLO-BASED ANALYSIS OF THE PHOTON BEAM FLUENCE WITH AIR GAP THICKNESS BETWEEN LINAC HEAD EXIT WINDOW AND PATIENT'S SKIN IN RADIOTHERAPY TREATMENTS

Linear accelerators (Linac) are used in radiation therapy treatment and its technology improvement ensures high dosimetry quality that should be conserved for high radiotherapy efficiency. However, does the air gap between the exit window of Linac head and patient's skin alters the physical properties of the photon beam? The objective of this study is to assess the physical properties changes of photon beam fluence according to air gap thickness under the Linac head. The air gap under the Linac head is the last material in the photon beam path; it induces alterations in the beam quality before reaching the patient's skin. The Varian Clinac 2100 head and the air gap up to the phantom surface are modelled using Monte Carlo BEAMnrc code; the nominal beam energy is 6 MV. The BEAMDP code is used to extract the photon fluence. The photon beam fluence is affected by the air gap under Linac head and decreases by six times due to the photon beam attenuation with air gap thickness; in addition to increasing of beam contamination by scattered photons and electrons. Thus, the air gap induces the beam quality deterioration which is evaluated in terms of photon fluence with air gap thickness. To remove the particles contaminations and conserve integrally the photon beam quality, the number of the photon interactions with air atoms should be as low as possible under Linac head up to patient's skin and ensure a higher quality of the radiotherapy treatment of deep tumour.

Keywords: air gap, Linac head, Monte Carlo simulation, photon beam quality, BEAMnrc code.

1. Introduction

At the entrance of the target volume, during the radiotherapy treatment of cancer, the photon beam composition is very crucial for the treatment quality. The photon beam should be homogenous in energy and particles type: photons only or electrons only. At the phantom surface, in addition to primary photons, the beam contains the electron contamination, the positron contamination and the scattered photons (of low energy) [1]. These particles deteriorate the dosimetry quality and subsequently have negative effects on the radiotherapy treatment quality [2].

The air gap is the last material in the photon beam path before reaching the patient's skin. Under linear accelerator (Linac) head, the air gap can alter the delivered dose by photons interaction with air atoms [3]. The specific features of the air gap effects on the physical properties of the photon beam depend on the air atoms number (pressure) between Linac head and patient's skin [4]. Therefore, it is important to determine the changes in these properties of the beam with air gap thickness and its effects on the dosimetry quality and subsequently on the radiotherapy treatment quality. The air gap effects on the beam are assessed by the photon interactions with air atoms that will be more negative if the particles contamination number is higher and their energy is lower [5].

The knowledge of characterizations of clinical beams is essential for dosimetry and development of accurate dose calculation algorithms in the clinical treatment planning systems (TPS) and thereafter for the overall technology development of Linac. The Monte Carlo simulation is a technique that provides a detailed energetic investigation as the spectral distribution and the beam fluence and a detailed dosimetric calculation as the percentage depth dose (PDD) output of Linac head [6]. These methods have been used extensively in medical physics for studying radiation therapy [7, 8]. They can be used to obtain information about the characterizations of the beam by analysing the dose distribution, the output factors and the beam energy [9].

The dosimetry quality management is recommended by many international institutions to survey instantaneously the external beam radiotherapy treatment [10, 11]. Beam quality is directly related to Linac head performance for producing the clinical beams to ensure a higher radiotherapy efficiency [12]. The beam quality study aims to improve the technology of the Linac head and its performance to produce the clinical beam of high quality in cancer treatment [13, 14].

In this study, we investigate the effects of the air gap on the beam quality in terms of photon fluence at different points in the beam path using the Monte Carlo method, which is used to simulate the Linac head and the air gap. The dosimetry quality analysis focuses on the photon beam characterizations at water phantom surface for checking in radiotherapy quality in terms of the photon fluence at the entrance of the target volume of cancer.

2. Materials and methods

2.1. Monte Carlo simulation

In this study, the air gap is the last material slab that is traversed by the photon beam. It is localized between the Linac head and the water phantom surface (Fig. 1). In the Monte Carlo simulation, the air gap is subdivided into eight sub-slabs of the thickness of 7.5 cm.

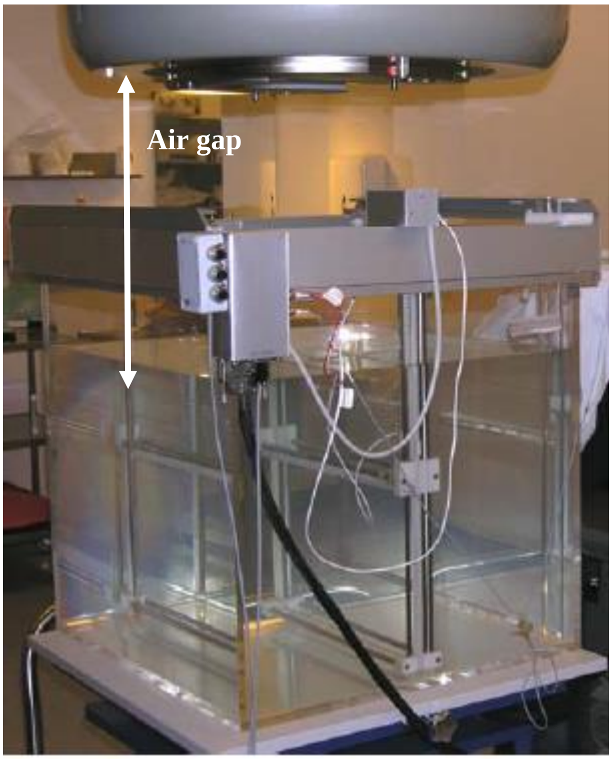


Fig. 1. Picture shows the Linac head, the water tank, and the air gap between them.

The geometry data of Varian Clinac 2100 model was supplied by the manufacturer (Varian Medical Systems, Palo Alto, CA). The 6 MV photon beam produced by the Linac is modelled using the BEAMnrc (Version 2013) simulation software. The irradiation field size is 10 × 10 cm^2 and the source to surface distance (SSD) is 100 cm. All parts of the Linac head including the target, primary collimator and flattening filter, monitor ion chamber, mirror, and X-Y jaws (secondary collimators) are modelled using modules provided by the code. The air gap also is an integral part of the Monte Carlo model of the Linac head; it is symmetrical around the central beam axis and simulated as a material slab.

The global cut-off energy for electron and photon particles are set to 0.7 MeV and 0.01 MeV, respectively. To increase the number of photons generated in the target, Directional Bremsstrahlung Splitting (DBS) is used as a variance reduction technique and it is 1000.

Fig. 2 shows the built Monte Carlo geometry of the head of Varian Clinac 2100 by BEAMnrc code and the air gap under the head for a field size of 10 × 10 cm^2.

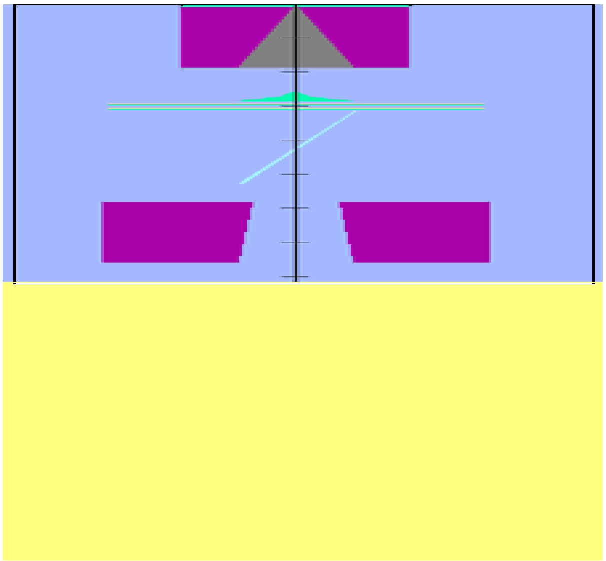


Fig. 2. Monte Carlo geometry of Varian Clinac 2100 in XZ plan generated by BEAMnrc and the air gap (yellow colour) under the Linac head. (See color Figure on the journal website.)

The histories number used in BEAMnrc is $2 \cdot 10^7$. This number is sufficient to generate a dose statistical uncertainty of 1 % and is as determined in other previous studies [15]. By the step of 7.5 cm, the scoring plan for phase-space files (PSF) is moved toward water phantom. Thereafter, the photon fluence is determined for sub-slab of the air gap of the thickness of 7.5, 15, 22.5, 30, 37.5, 45, 52.5 and 60 cm.

2.2. Monte Carlo simulation validation

One way to validate the Monte Carlo simulation of the Linac head is to evaluate the dosimetry of the clinical photon beam in terms of percentage depth dose (PDD) curves and dose profiles curves. By comparison of calculated dose distributions with experimentally measured dose distributions, the Monte Carlo simulation is validated using the gamma index method [16]. The gamma index criterion is 3 % for dose deviation and 3 mm for distance to the agreement. The gamma index values which are ≤ 1 define the agreement between measured and calculated dose distributions along with the depth for PDD and the off-axis for dose profile in the water phantom. Thereafter, the gamma index acceptance rate is determined to evaluate the agreement between both compared dose distributions [17]. The measurements of dose were performed using PTW equipment [18].

3. Results and discussion

The gamma index rate is determined for PDD and dose profiles for Varian Clinac 2100 and it is compared to the tolerance limit recommended by International Atomic Energy Agency (IAEA) in Technical Report Series (TRS) No. 430 and in Technical Documents (TECDOC) No. 1540 [19, 20]. The Monte Carlo simulation validation of Varian Clinac 2100 is a subject of one of our previous scientific publications [21]. It is more accurate by approximately 99 % for PDD and dose profile in comparison with previous studies [22]. The primary electron source above the target is monoenergetic with the energy of 6.52 MeV, the radial spread is Gaussian with the full width at half maximum (FWHM) of 1.4 mm, and the mean angle spread is 1 °.

Using the BEAMDP code, the photon beam fluence is extracted based on phase space files (PSF) generated by BEAMnrc code [23]. Fig. 3 shows the photon fluence profiles as a function of off-axis distance for each sub-slab of the air gap with different thicknesses from 0 to 60 cm by the increment of 7.5 cm.

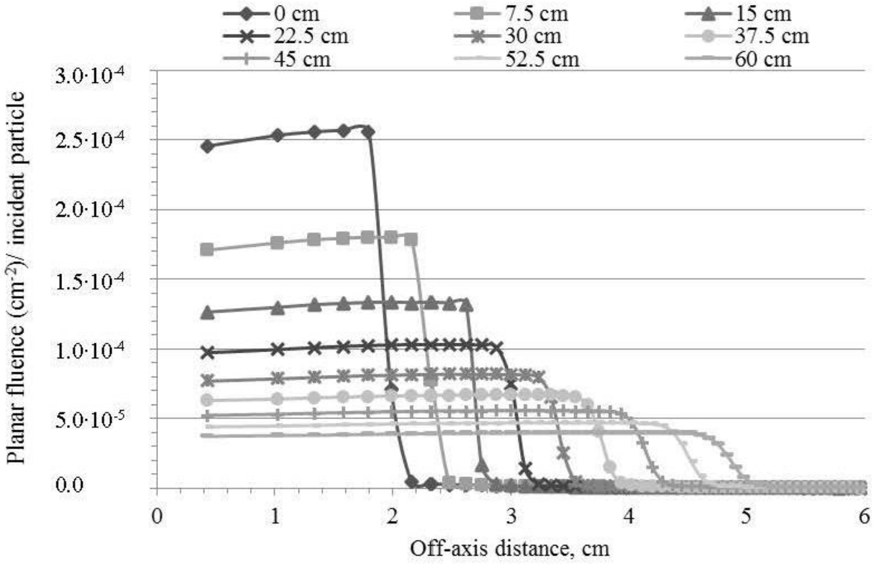
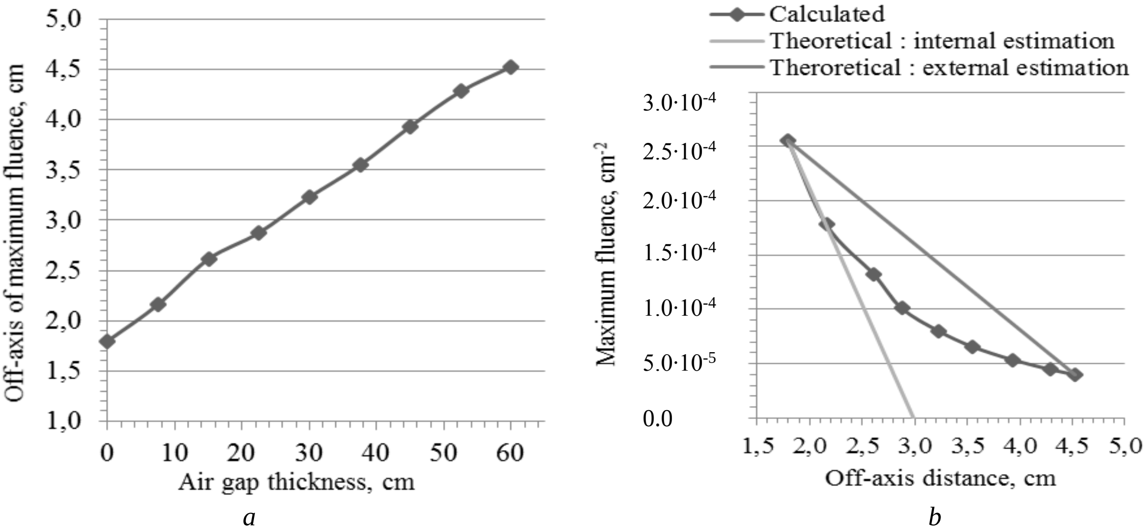


Fig. 3. Photon fluence profiles with the thickness of the air gap as a function of off-axis distance.

We notice from Fig. 3, the photon beam fluence decreases according to the thickness of the air gap and the maximum fluence moves toward the increasing off-axis distance. Fig. 4 gives the off-axis distance variation with thickness and the maximum of the photon beam fluence variation with off-axis distance and the theoretical estimation bordering the maximum variation with off-axis distance.



a *b*

Fig. 4. Off-axis of the maximum of the photon fluence as a function of air gap thickness (*a*), the maximum of the photon fluence and the theoretical estimation as a function of off-axis distance (*b*).

The off-axis of the maximum of the beam fluence varies linearly with air gap thickness and it is natural due to beam edge limited by the flatness of the inner surface of jaws (see Fig. 4, *a*). For evaluating the variation of the maximum of the beam fluence at the beam edge, Fig. 4, *b* gives the variation of the maximum of the beam fluence with off-axis distance. The maximum of the beam fluence decreases with off-axis distance but this decreasing is not in a linear manner.

At the beam edge, for assessing the impacts of the air gap on the photon beam fluence, we have proceeded to estimate theoretically the maximum variation of the beam fluence with off-axis distance. Therefore, the maximum of the beam fluence should vary with off-axis distance in a linear manner because the inner surface of jaws is flat and it limits the photon beam to travel in the straight line.

We have evaluated two theoretical estimations: internal estimation and external estimation. The internal estimation gives the information about the nearest variation line to the central beam axis and the external estimation gives the information about the farthest variation line of the maximum of the photon fluence at the beam edge (see Fig. 4). Near the patient's skin, the deviation between two lines is very big and induces, with off-axis distance, the alteration of dosimetry quality. These alterations should be taken into account in the radioprotection management and the radiotherapy treatment quality inside the treatment room.

Fig. 5 gives the variation of the maximum of the photon beam fluence with the thickness of the air gap.

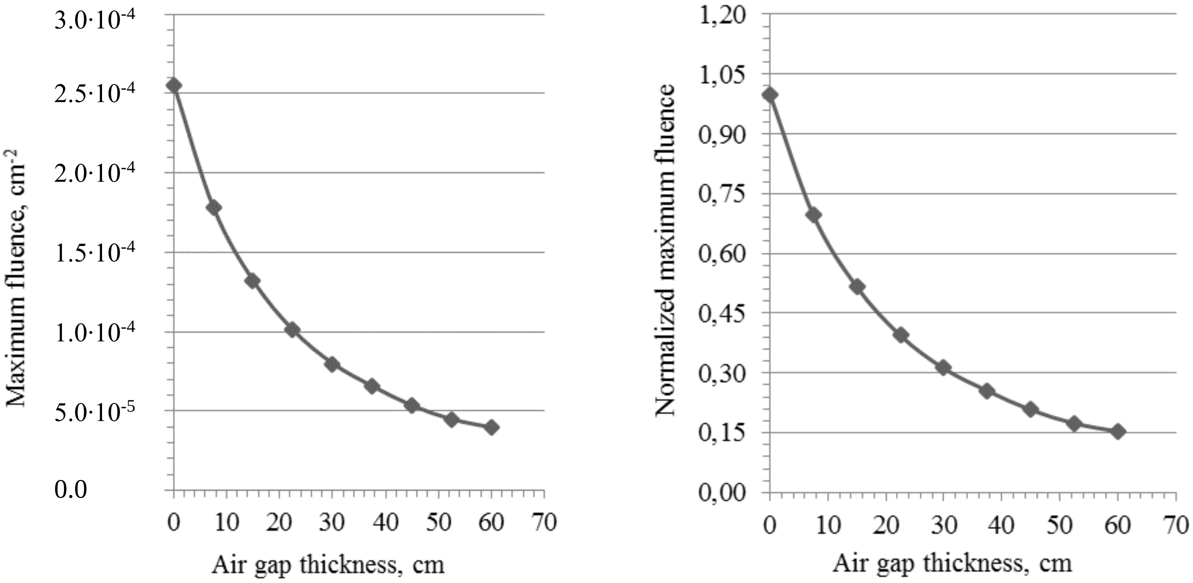


Fig. 5. Maximum of the photon beam fluence as a function of the thickness of the air gap.

The maximum fluence decreases according to the thickness of air gap due to the photon beam attenuation in-depth and the maximum fluence decreases up to 15 % considering an air gap thickness of 60 cm (see Fig. 5). This finding is natural and its impact on dosimetry is very negative due to the reduction of energetic photons number and to the increase of the amount of electrons contamination and photons of low energy (scattered photons) for the deep tumour treatment. The quality of dosimetry is deteriorated by decreasing the number of energetic photons in parallel of the increase of the amount of the particles contamination by photon interactions with air atoms.

Therefore, the maximum of the photon fluence does not vary linearly with off-axis distance due to the flatness of the inner surface of jaws. With the thickness of the air gap, the maximum of the photon beam fluence is attenuated with thickness. At the beam edge, both off-axis distance and thickness of the air gap affect negatively and jointly the dosimetry quality under the Linac head. In this work, we have described qualitatively the air gap impacts on the dosimetry quality in terms of photon fluence with off-axis distance and with the thickness of air gap between the exit window of the Linac head and patient's skin. These results are in consistency with previous studies [24, 25].

4. Conclusion

The air gap between the exit window of Linac head and patient's skin induces the dosimetry alteration that increased with air gap thickness. The dosimetry alteration with air gap could induce more complexes problems in radiotherapy treatment of deep tumour and radioprotection quality inside the treatment room.

Our study can be a basic for radiotherapy quality enhancement in Linac future generation in framework to improve the treatment efficiency by reducing the air gap effects on the beam dosimetry quality, which is studied in our previous work [3].

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

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МОНТЕ-КАРЛО МОДЕЛЮВАННЯ ТА АНАЛІЗ ІНТЕНСИВНОСТІ ФОТОННОГО ПУЧКА ЗАЛЕЖНО ВІД ТОВЩИНИ ПОВІТРЯНОГО ПРОМІЖКУ МІЖ ВИХОДОМ ЛІНІЙНОГО ПРИСКОРЮВАЧА І ШКІРОЮ ПАЦІЄНТА В РАДІОТЕРАПІЇ

Лінійні прискорювачі використовуються при лікуванні променевою терапією, і вдосконалення відповідних технологій забезпечує високу якість дозиметрії, яку слід зберегти для високої ефективності терапії. Однак чи змінює повітряний проміжок між вихідним вікном прискорювача та шкірою пацієнта фізичні властивості фотонного пучка? Завданням цього дослідження є оцінка зміни фізичних властивостей фотонного потоку залежно від товщини проміжку. Повітряний проміжок при виході з прискорювача є останнім матеріалом на шляху пучка; він змінює якість пучка на вході в шкіру пацієнта. За допомогою Монте-Карло коду BEAMnrc було промодельовано вихід прискорювача Varian Clinac 2100 та повітряний проміжок до поверхні фантома; номінальна енергія пучка становила 6 МВ. Код BEAMDP використовувався для обчислення потоку фотонів. Потік ослаблюється до 6 разів залежно від товщини проміжку; крім того, при збільшенні товщини збільшується забруднення пучка розсіяними фотонами та електронами. Таким чином, повітряний проміжок погіршує якість пучка. Щоб усунути забруднення та зберегти загальну якість фотонного пучка, число актів взаємодії фотонів з атомами повітря від виходу з прискорювача і до шкіри пацієнта повинно бути якомога меншим; це забезпечить більш високу якість лікування глибоких пухлин променевою терапією.

Ключові слова: повітряний проміжок, вихід лінійного прискорювача, моделювання методом Монте-Карло, якість фотонного пучка, програма BEAMnrc.

Надійшла/Received 30.01.2019