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ARTICLE

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Representation and illustration of the initial parameters in GATE 8.1 monte carlo simulation of an Elekta Versa-HD linear accelerator

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ABSTRACT

The purpose of this study is to validate GATE 8.1 Radiotherapy Monte Carlo (MC) simulation of a 6 MV Elekta Versa-HD linear accelerator at King Abdulaziz University Hospital (KAUH). The simulation data using GATE 8.1 was benchmarked against measured data at KAUH. The simulation comprises treatment head, Multi-Leaf Collimators (MLCs), and homogeneous water phantom, whereas the measured data was performed using MP3 phantom and PTW 31,010, 0.125 cm^3 Semiflex Chamber. Dose depth distribution and dose profiles were carried out at three different field sizes 10x10, 20x20, and 30 × 30 cm^2. The calculated $TPR_{20,10}$ for the simulated data was found to be 0.658, 1.1% less than the measured $TPR_{20,10}$ which was found to be 0.666. The obtained results indicate good agreement between the simulated and measured data, where Gamma Index 3%/3 mm criteria reached values of 97% and 90% for relative dose and dose profiles, respectively.

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1. Introduction

Monte Carlo (MC) simulation for radiation transport and usage in medical physics and dosimetry have increased rapidly and been proven to be a safe and fast approach to innovation and development in radiation therapy (Ahnesjö and Aspradakis, 1999; Reynaert et al., 2006; Sardari et al., 2010; Seco & Verhaegen, 2013). Therefore, (MC) codes have been successfully employed by many research groups in radiation therapy. Hence, analytic methods have been replaced by MC methods for treatment planning in radiotherapy (Chetty, 2008; Verhaegen & Seuntjens, 2003).

The MC technique proved to be the most efficient in simulating various radiotherapy applications (Andreo, 2018). There are many MC codes such as PENELOPE, EGSnrc, MCNP, XVMC, FLUKA, and GATE. Each one has its own purpose and application. GATE in particular has demonstrated to be of great use in radiotherapy (Agostinelli et al., 2003; Allison et al., 2006). GATE is an open-source freely available Monte Carlo simulation toolkit. Initially, GATE was developed to deliver a realistic simulation for positron emission tomography 'PET' and single-photon emission computed tomography 'SPECT' (Jan et al., 2004). It has been developed recently for all its components to simulate any geometry, materials, particles, and most of the physics processes involved in particle interactions. Several features were added later on, extending the toolkit to include radiation therapy and dosimetry applications (Jan et al., 2011; Papadimitroulas et al., 2012).

A significant amount of studies were conducted to validate GATE and demonstrate its potential for radiotherapy (Sarrut et al., 2014). Aitelcadi et al. used GATE to model Clinac2300C/D 6 MV photon beam Aitelcadi et al. (2018). In his validation study, more than 96% of the points passed the gamma index 2%2 mm criterion, indicating a good agreement between simulation and measurements. Papadimitroulas showed GATE to reliable and efficient in various dosimetry, brachytherapy, and particle therapy applications Papadimitroulas (2017). Several other studies were carried out to validate GATE in dosimetry (Horitsugi et al., 2012; Laoues et al., 2015), proton therapy (Grevillot et al., 2011a; Zarifi et al., 2019), and brachytherapy (Thiam et al., 2008). Many studies sufficiently showed GATE to have great potential in aiding treatment planning systems (Arbor et al., 2019) and in IMRT treatment planning (Benhalouche et al., 2013).

The work presented in this paper intended to simulate a 6 MV Elekta Versa-HD linear accelerator. The simulation data is benchmarked against measured data at King Abdulaziz University Hospital (KAUH). The main purpose of this work is to validate the simulation. This work should lead to further investigations to enhance treatment delivery and planning.

2. Materials and methods

2.1. Reference data

Reference data for Versa-HD Elekta Linac were obtained at King Abdulaziz University Hospital

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'KAUH'. Dosimetric distribution measurements were carried out for 6 MV photons and field sizes 10x10, 20x20, and 30 × 30 cm^2 using MP3 Water Phantom System and PTW 31,010, 0.125 cm^3 Semiflex Chamber. The data was acquired at a source-skin distance 'SSD' of 90 cm and the field size was defined at 10 cm depth.

2.2. Linac components modeling

The linear accelerator modeling was based on the specifications provided by the manufacturer, see. It should be noted that minor inaccuracies in modeling some components in terms of relative position or dimensions could noticeably alter the beam properties. For example, initial simulation runs showed that misplacing the flattening filter by 5 mm farther from the target causes the beam to lose uniformity more rapidly for higher depths and field sizes. Therefore, components that affect the beam properties should be modeled with the highest possible precision.

The multi-leaf collimator (MLC) and the backup-Y collimator have a somewhat complicated geometry. Therefore, both components were designed as 3D stereolithography models (STL) using the computer-aided design software SolidWorks (Massachusetts, USA) and imported into the simulation as tessellated volumes. This feature in GATE allows an easier and accurate representation of complex geometry.

2.3. Linac beam modeling

The electron mean energy and the target spot size were found to have a significant effect on dose profiles and percentage depth dose (Fix et al., 2005). Verhaegen and Seuntjens (2003) proposed varying the electron beam energy and spot size until the simulated depth dose, and dose profiles match the measured ones. This procedure has been used to determine the primary electron beam characteristics for each photon energy.

The primary electron beam was assumed to have a gaussian energy distribution. The mean energy was varied by a 0.1 MeV step, ranging from 5 to 7 MeV. The energy distribution full width at half maximum 'FWHM' was set to 3% of the mean energy as recommended by Fix et al., (2005). The focal spot size was also assumed to have a gaussian distribution with the FWHM being varied from 1 to 5 mm to determine the optimal spot size. Figure 1

The simulation is split into two stages. The first stage is considered patient independent as the beam is unaffected by the field size or any patient-related specifications. It starts with the generation of X-ray photons as a result of the electron beam hitting the target. The generated X-ray photons travel through several components of the accelerator until reaching the phase space volume located above the secondary collimators. This cylindrical volume, which is 1 nm thick and 10 cm in radius, serves as the medium to collect the photon flux, position, direction, and energy information and store it in a phase space file. Each simulation run resulted in storing at least 60 million photons (Deng et al., 2000; Grevillot et al., 2011b). The use of the phase space method increases the execution time per run considerably. Therefore, all the patient-independent simulations were executed in the GateLab computing grid infrastructure (Camarasu-Pop et al., 2013), reducing the execution time from days to a few hours per run.

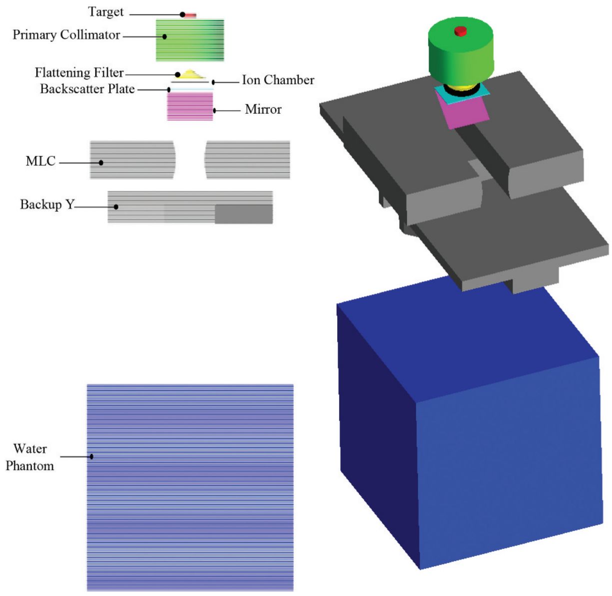

Figure 1. A schematic diagram of Versa-HD linear accelerator. The components dimensions are not to scale.

The second stage starts with recalling the stored phase space data to simulate the patient dependent part. The beam emitted from the phase space volume is shaped by the secondary collimators into the desired field size. The beam then strikes the 50x50x50 cm^3 water phantom located at an SSD of 90 cm. A dose actor consisting of 5x5x5 mm^3 dose scoring voxels is attached to the phantom to collect the dose distribution and determine uncertainty (Jan et al., 2011; Sarrut et al., 2014). The dose was calculated using 4 billion particles, keeping the statistical uncertainty below 2.5% for all dose calculating voxels with a relative dose ≥0.2. Since it is not yet possible in GateLab to run simulations where a phase space file is used as an input, all second stage simulations were run locally. The total execution time for all second stage simulations was around 10 days.

Interactions were simulated in GATE using the standard electromagnetic package (Grevillot et al., 2011b; Poon & Verhaegen, 2005), which provides models accurately describing the interactions of photons, electrons, and positrons in the energy range 1 keV-10 PeV (Amako et al., 2005). The cutoff was set to 1 mm for photons, electrons, and positrons in the water phantom. Bremsstrahlung splitting technique was used to speed up the first stage simulations (Kawrakow, 2005; Kawrakow & Walters, 2006). Bremsstrahlung photons generated by electrons hitting the target were sampled 100 times, with each particle weighting 1/100 (Grevillot et al., 2011b).

2.4. Simulation assessment

The simulation generated output is in the form of tomographic images representing the 3-dimensional dose distribution and uncertainty within the water phantom. Depth dose and lateral dose at depths 5, 10, and 20 cm distributions are extracted from the images. Depth dose distributions are then normalized to the maximum dose of each distribution, while the lateral profiles are normalized to the average dose at the center of the profile.

Gamma-index γ is one of the most commonly used methods for determining the agreement between simulated and measured data (Hussein et al., 2017; Low & Dempsey, 2003; Low et al., 1998). It can be used to determine the optimal electron energy and spot size by comparing the simulated dose for each electron source with the measured data.

Additionally, the mean point-to-point dose error was estimated, using the equation:

$$\varepsilon_p = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|d_i - dref_i|}{dref_i}\right) \quad (1)$$

where ε_p is the mean point-to-point error, N is the number of points evaluated, i is the index of the evaluated curve point, d_i is the simulated dose at point i and $dref_i$ is the measured dose at point i.

The low number of primaries at higher depths and at the tail of the penumbra result in relatively low doses in these areas. This leads to significant errors regardless of how good the simulated dose agrees with the measured dose at the same point. Therefore, it is useful to normalize errors to the maximum dose to reduce the weight of errors at low dose areas and increase it at high dose areas, as follows:

$$\varepsilon_n = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|d_i - dref_i|}{dref_{max}}\right) \quad (2)$$

where $dref_i$ is the maximum measured dose. Furthermore, the tissue phantom ratio at depth of 20 and 10 cm for a 10 × 10 cm^2 fields ($TPR_{20,10}$) is determined using the empirical relationship suggested by Followill et al. (1998):

$$TPR_{20,10} = 1.2661\left(\frac{PDD_{20}}{PDD_{10}}\right) - 0.0595 \quad (3)$$

The estimation of gamma-indices and errors can be considered as a time-consuming process given the fact that it should be carried out for every electron energy and spot size. Therefore, a MATLAB function was developed to accelerate the process. The function imports all the output data and then identifies the electron energy and spot size associated with each output file from the file label. Afterward, depth dose and dose profiles are extracted and normalized. Finally, gamma-indices and errors are estimated. The gamma-index tolerance evaluation criteria was adjusted to 3% 3 mm and any points with a relative dose of less than 0.2 were ignored. The total computation time for all simulations using this MATLAB function was less than 5 minutes on a 2.6 GHz Intel i7-6700HQ processor.

3. Results and discussion

In this study, a full detailed simulation of Elekta Versa-HD linear accelerator of 6 MV photons was carried out. The distribution of photons emitted from the phase-space layer is depicted in Figure 2. The effect of the flatting filter can be seen clearly in the middle of the photon beam distribution in Figure 2A. In Figure 2B synchronization and uniformity of the lateral edges of the 2D photon, beam distribution is clear with relatively low intensity at the center than adjacent area.

The beam emitted from the phase-space is shaped by the secondary collimators before reaching the water phantom. Figure 3 shows the radiation intensity distribution at the surface of the phantom for 10 × 10 cm^2 field size.

The results showed 6.4 MV electron energy and spot size of 4 mm to produce the highest agreement with experimental measurements. Several other electron energies showed less but still acceptable agreement for depth dose with experimental measurements for

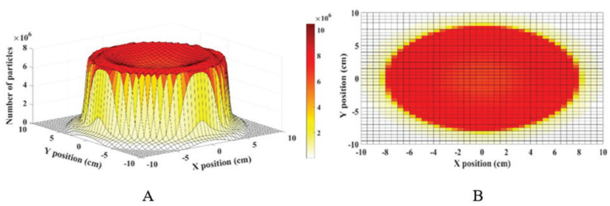

Figure 2. The intensity distribution of the radiation emitted from the phase space volume.

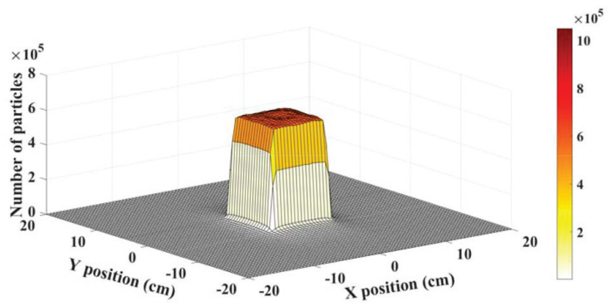

Figure 3. Radiation intensity distribution at the surface of the phantom for 10 × 10 cm^2 field.

10 × 10 cm^2 field size. Nevertheless, most of these energies showed relatively poor agreement with larger field sizes.

The detailed gamma index and error percentages (ε_p and ε_n) for depth dose are shown in Table 1. At least 97% of the points passed the 3%3 mm criterion, with 30 × 30 cm^2 showing the highest error and lowest agreement.

The lateral profile data presented in Table 2 showed lower agreement and higher error percentages relative to the depth dose data. Nevertheless, at least 90% (92% on average per field size) of the lateral profile points pass the gamma index criterion. The calculated $TPR_{20,10}$ for the simulated data was found to be 0.658, 1.1% less than the measured $TPR_{20,10}$ which was found to be 0.666.

Table 1. Simulation depth dose assessment for different field sizes. γ, ε_p and ε_n are all given in percent.

Field Size (cm)	γ	ε_p	ε_n
10x10	100	1.2	0.6
20x20	100	1.2	0.6
30x30	97	1.3	0.7

Table 2. Simulation lateral dose profiles assessment for different field sizes and depths. γ, ε_p and ε_n are all given in percent.

Field Size (cm)	Depth (mm)	γ	ε_p	ε_n
10x10	50	90	2.7	1.3
	100	100	1.9	1.3
	200	91	2.9	2
20x20	50	95	4.4	3.9
	100	90	3.8	3.1
	200	91	3.9	3.1
30x30	50	93	2	1.8
	100	93	3.9	3.0
	200	94	4.8	3.9

Figure 4 shows excellent agreement between the simulated and the measured data at three different field sizes 10x10, 20x20, and 30 × 30 cm^2. The Gamma index technique showed at least 90% agreement of all points of the simulation at 3% and 3 mm. However, it shows at least 97% agreement for all points in percentage depth dose at all three field sizes. The majority of the mismatch shown on the edges of the lateral doses, Figures 4C and Figures 4D, are possibly due to the MLC. The manual states that the MLC is somewhat tilted with no further information on the angle. Hence, the authors consider that is the likely reason behind the misalliance on the dose profile. Moreover, this is more evident with larger field sizes.

Various performance parameters were evaluated in this study such as dose along depth, Figure 4A and lateral dose at three different depths, Figures 4 (B, C, and D). Depth-dose profile simulations result, Figure 4A, were in adequate agreement with reference measurements performed in water at hospital. Dose at maximum received deviations less than 0.3%, 0.5%,

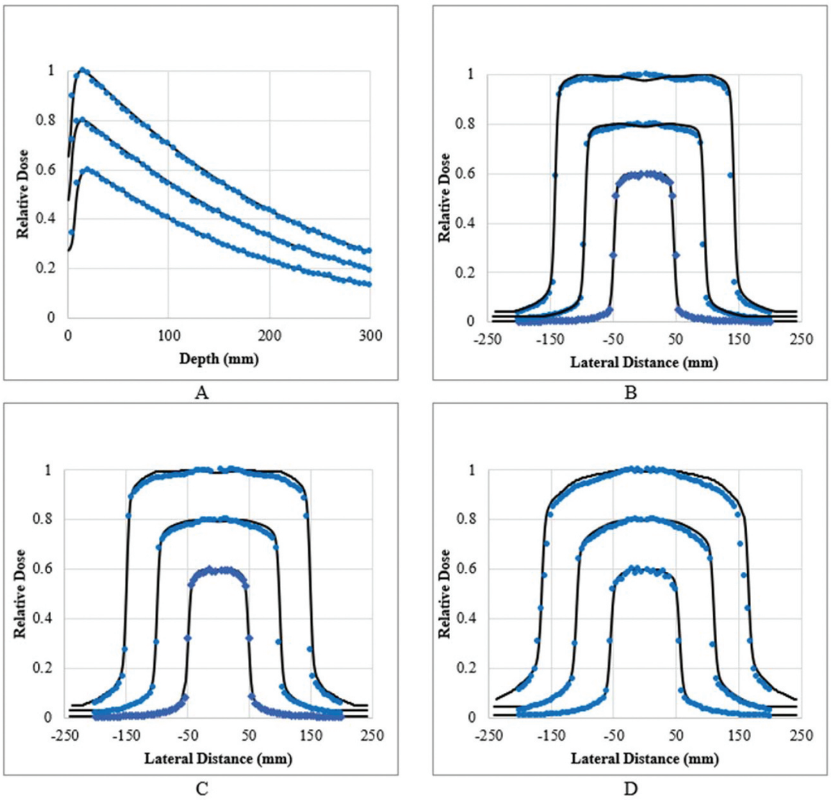

Figure 4. Relative measured and simulated dose (A) along depth, (B) lateral profiles at 5 cm depth for different field sizes, (C) lateral profiles at 10 cm depth for different field sizes, and (D) lateral profiles at 20 cm depth for different field sizes. Measurements are represented in smooth lines while simulations are represented by dots. 10x10, 20 × 20 and 30 × 30 cm^2 results are normalized to 0.6, 0.8 and 1 respectively.

0.8% at three different filed sizes 10x10, 20 × 20 and 30 × 30 cm^2, respectively.

The flattening filters position accuracy and geometry modeling play a significant role in influencing the dose distribution and behavior. It is noteworthy that Figure 4 B, C, and D showed few interpretations of the shape effect as to compare the measured results with simulation accuracy modeling. When comparing simulated and measured ranges, not only the exact position and dimension of the filters accounts for range differences, but the simulation time and history for uncertainty of the result influences the range as well.

4. Conclusion

The main goal of this research was to validate GATE v8.1 capability in simulating a Versa-HD linear accelerator. The modeling of the accelerator geometry was carried out with the highest possible precision.

The procedure used in this study to validate the Versa-HD linear accelerator although considered efficient can be also considered somewhat impractical. The patient independent part of the validation process requires simulating various electron energies, which without the use of a computing grid could take a very long time. The reduction of the simulation time is significant with a computing grid, but numerous simulations must be conducted before finding the best parameters. This issue raises the question about the possibility of using a mathematical algorithm that could allow researchers to converge to the best parameters with fewer simulations.

The results showed that electron energy of 6.4 MeV and a spot size of 4 mm produced results that agreed most closely with measurements. These results were assessed using the gamma-index technique. More than 90% of the points passed the 3% 3 mm criteria for all curves with curves along depth showing at least 97% agreement.

Although VERSA HD was modeled successfully in GATE, additional investigations will be carried out to improve the validation further and extend it for more field sizes and energies.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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