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Monte Carlo simulation of Electron Beams; Influential Parameters and Potential Sources of Simulation Faults

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ABSTRACT

High-energy photon and electron beams were accurately simulated by Monte Carlo code. Electron simulation is not easy due to their light weight and their scattering nature. Moreover, because of the commercial value of the detailed specifications of the accelerator parts, manufacturers are usually reluctant to provide the information with the necessary details for modelling.The aim of this report is to study the effect of slight alterations in simulating the intrinsic beam parameters and Linac configurations. The electron beams of the ELEKTA SL18 were simulated for different energies and field sizes using BEAMnrc. The output phase space files were used as input sources on a water phantom created using DOSXYZnrc. Different sources of systematic sources of errors in the simulation were investigated by slight alterations in beam and phantom parameters including the electron energy width of the beam, the source to surface distance and the voxel size, in addition to alterations in some Linac components such as, the walls of the scattering foils, the configuration of ionization chamber and the mirror, the jaws opening in addition to the materials of applicators. This was performed for a 10x10 field for a low energy (4MeV), moderate electron energies (8 MeV and 15 MeV) and high electron energy (18 MeV) at different source to surface distances (SSD). This work shows the necessity of the accuracy of simulating some of the beam parameters, the water phantom and the different Linac configurations and explains systematic errors that arise from slight alterations in these values. Percent depth dose curves are more influenced by accurate modelling of the different parts of the linear accelerator, especially the scattering foils, the monitor ionization chambers and the applicator materials. Beam parameters, source-to-surface distance, voxel sizes as well as some Linac components such as scattering foil walls, jaws opening and material of the applicators affect the off-axis dose distributions especially in the plateau and the shoulder regions.

Key words: **Monte Carlo, electron beams, beam parameters, LINAC components.**

1. Introduction

Electron beam therapy is an important radiation therapy modality for treatment of superficial tumors. Treatment planning of electron beams is more complicated than photon beams due to variations in beam productions, the scattering of low energy electrons and the presence of contaminant photons [ICRU 2004, Gerbi 2006, Khan 1992 and Hogstrom 2006].

Therefore accurate beam modeling is very crucial for accurate dose calculations within the patients. Monte Carlo (MC) calculations are widely accepted as the most accurate means for dose calculations and are expected to produce errors within 2%/2mm in dose as opposed to analytical methods where errors of 5%/5mm or more were reported. [Rogers 2002, ICRU 1987, Anoltak 2002, Chetty 2007, Ding 2005, Jiang 2000, Ma 1999]

The electron beam energy spectrum emerging from the accelerator treatment head is complex and may differ appreciably among accelerators from different manufacturers and among models of accelerator from the same manufacturer depending on the design of the treatment head. [Followill 2004] Because of the commercial value of the detailed specifications of the accelerator parts, manufacturers are usually reluctant to provide the information with the necessary details for modelling. Thus, approximation of the initial beam is often used in MC simulations, although this can lead to discrepancies with measured data. [Jiang 2000, Followill 2004]

The most basic information required for a MC simulation of a treatment head is the specifications of the accelerator parts, such as their locations, dimensions and materials. The major sources of error are statistical errors or uncertainties resulting from simulation of the accelerator treatment head and those resulting from the fluctuations in phantom/patient dose calculations. In this paper the effects of minor alterations in the simulation of beam and phantom parameters as well as Linac configurations on both the percent depth dose and dose profiles are investigated. This would help future researchers in the field to point out the possible mistakes in their simulations).

2. Materials and Methods:

Linac Simulation: The electron beams from ELEKTA SL18 were simulated according to the manufacturers' data on the treatment head geometry using BEAMnrc/EGSnrc [Rogers 2004, Kawrakow 2004, Kawrakow 2000]. The accelerator head was built from the following component modules (CMs) CONESTACK, which consists of a stack of truncated cones, surrounded by a cylindrical wall, was used to simulate the exit window and the primary scattering foils. It was used for the secondary scattering foils for low and moderate-energy beams. CONS3R was used for the primary collimator and the secondary scattering foils for high-energy beams. The distance between the primary and secondary scattering foils varied with the energy of the incident beam. The ionization chamber, jaws and applicators were simulated using IONCHAMB, JAWS and APPLICAT component modules respectively

The output phase space file was used as an input source on a water phantom created using DOSXYZnrc [Walters 2004] to produce a dose output file ".3ddose" which contains the information about the simulation geometry and the calculation results in a format that can be read by STATDOSE to generate xvgr/xmgr plots (percent depth dose (PDD), normalized to Dmax, and the dose profiles at Dmax) for comparison purposes.

The choice of energy threshold below which the histories of electrons and photons (global ECUT and PCUT) or their product knock-on electrons and Bremsstrahlung photons (AE and AP) are terminated, was the same for both Linac and phantom simulations. ECUT and AE were both set to 0.521 MeV. PCUT and AP were set to 0.01MeV. Boundary crossing and

electron step-size algorithms were chosen to be PRESTA1 and PRESTA2 respectively. A mono-energetic beam from (ISOURCE =19), which involves a circular beam with 2D Gaussian distribution was chosen for our beam simulations. No photon or electron splitting was performed. In order not to reject any low energy electrons the global ESAVE was set to zero. A cluster of five computers with different processor speeds was used for parallel processing. The number of particles used for simulation ranged from 200-500 million particles depending on the energy and field size. This number decreased with increasing beam energy and field size. In phantom simulations the histories were chosen so that the particles from the phase space files were not recycled more than 30 times to avoid unnecessary uncertainties. Fine-tuning of the beam was performed until a good match in relative depth dose and dose profiles between measurements and calculation was reached. This included alteration in the beam energy as well as energy distribution. It has been reported that the full width at half maximum (FWHM) of the intrinsic energy spectrum is about 5% and 10% of the most probable energy for accelerators of the travelling wave and standing wave types respectively [Bjork 2002]. This value did not produce a satisfactory match between the measured and the calculated percent depth dose. The value was increased until a better match was produced. The result Linac and component modules are referred to as verified Linac, or verified (named) component modules, respectively

Effects of Beam and Linac Configurations Alterations: The effect of small alterations in initial beam parameters, and configuration of some accelerator components was investigated for 10x10 fields using 4 MeV, 8 MeV, 15 MeV and 18 MeV electron beams as follows:

2.1 Energy Distribution of the Initial Beam: The effect of decreasing and increasing the FWHM beyond the verified values was studied on both PDD and dose profiles. This is done because the value that produced a good match between measured and calculated central axis PDD was more than the suggested 10% of the most probable energy [Bjork 2002].

2.2 Source-To-Surface Distance (SSD): from a practical point of view, a longer distance between the collimator and the patient is often preferable; otherwise the collimator might collide with the shoulder of the patient when tumours in the neck region are to be treated [ICRU 2004]. The effect of SSD was investigated by locating the phantom immediately after the last scraper of the applicator i.e. at a SSD of 95 cm and at 100 cm and 105 cm respectively.

2.3 Voxel Size: Calculated dose is affected by the size of the scoring voxel. For MC calculations typical values in the scoring dimensions are voxel sides of 2-5 mm for field sizes greater than 3x3 cm2. Increasing the voxel size reduces the simulation time as well as the size of the output 3ddose files but may affect the statistical uncertainty [Chetty 2007]. A water phantom consisting of Cartesian voxels of water was simulated using DOSXYZnrc. Different voxel side dimensions: 2.5 mm referred to as small voxels, 5 mm referred to medium voxel size and 10 mm referred to as big voxels were used to study the effect of voxel size on both PDDs and dose profiles.

2.4 The Scattering Foils: SL18 has dual scattering foils that consist of a high-z (atomic number) material to broaden the beam into a Gaussian profile and a lower-z Gaussian-shaped foil that minimally scatters the electrons at the tail of the profile and maximally scatters electrons near the centre to flatten the field in the area of interest with a suitably sharp fall-off at the field edges. The effects of materials and dimensions of the scattering foils for mono-energetic and poly-energetic beams have been extensively studied elsewhere. [Bieda 2001, Schreiber 2005, Kainz 2005] No literature was found explaining the influence of walls of the scattering foils. For low and moderate energies of SL18 (up-to 15 MeV), the shape of the foils descends in an increasing diameter pattern, which allows simulation using the CONESTAK component module. This allows simulation of the walls. The situation is different for higher energies, 18 MeV and above, where it was necessary to use CONS3R that does not allow simulation of the walls or FLATFILT option that allows simulation of overlapping cones with varying diameters and simulation of the surrounding walls. In this paper the height of the walls of the scattering foils was altered and the foils were simulated without the walls to compare the PDDs and profiles generated with and without alterations.

2.5 The Ionization Chambers: Most Linacs have segmented ion chambers that allow monitor both beam intensity and uniformity [Brown 1999]. The monitor ionization chamber of the SL18 is made in form of thin layers of a light material separated by air gaps. This is embedded in a metal disk. Accurate simulation of the ionization chamber is not necessary in a simulation of photons were a good match between measured and calculated PDD and profiles was possible with a 1 cm thick water slab simulated by SLAB CM, which is relatively easy to simulate. This is not the case for electron beams, where all components on the beam direction are expected to influence the dose. Simulation of the ionization chamber was performed using IONCHAMB component module, SLAB of Mylar 0.072 cm thick, which represents the total thicknesses of the Mylar films within the ionization chamber, and CONSTAK. SLAB option was used to evaluate the possibility of simplifying the simulations and CONSTAK option was used because IONCHAMB module does not allow accurately simulating the different materials of the inner walls surrounding the different segments. Finally simulation was performed without the ionization chamber and the results were compared.

2.6 The Mirror: The light localizing system, which consists of the light source and a thin mirror, is used for field size definition within the patients. Despite the very small thickness of the mirror, being on the path of the electron beams, it may have scattering effects. The influence of the mirror was investigating by simulating the Linac with and without mirrors.

2.7 The Jaws: The jaws opening, which indicates the field size at a named SSD, usually 100 cm and the inclination of the jaws are automatically defined at the Linac monitor according to the applicator used and the energy. Using these values for x and y openings from the monitor of the Linac did not always produce a good match between measured and calculated profiles. Neither did calculations of the openings according to the opening of the upper scraper of the applicators or according to the required field size, 10x10 for example. The effect of altering the jaws opening was studied in this work.

2.8 The Applicators: In radiotherapy with high-energy electron beams, scattered radiation from the applicator influences the dose distributions in patients. The amount of radiation is dependent on the applicator design [van Battum 2003]. Electron applicators provided by ELEKTA are in the form of sets of diaphragms or scrapers with a thick base that is attached to the treatment head. This reduces the intensity outside the useful beam to less than 2%. In this paper the effect of two different materials: lead and aluminum, which are the materials for ELEKTA applicators, are investigated.

3. RESULTS

The effect of slight alterations on beam parameters and Linac configurations are summarized below:

3.1 Energy Distribution of The Initial Beam: Increasing the beam width from 10% of the most probable energy (referred to as small FWHM in the graphs) to the verified FWHM MeV slightly decreased the dose gradient and slightly increased the Bremsstrahlung tail for the different energies. More effect is noticed on the PDD of the high energy (18 MeV). A much smaller alteration is noticed with further increase in the FWHM. The increase in FWHM slightly affects the dose profiles where the flatness is reduced and the shoulder is depressed with a further increase in beyond the verified value, referred to as big FWHM. This can be seen more clearly for the small energy (4 MeV). The effect of energy width on PDD and dose profiles is demonstrated in Figure 1 below for 4 MeV and 18 MeV electron beams.

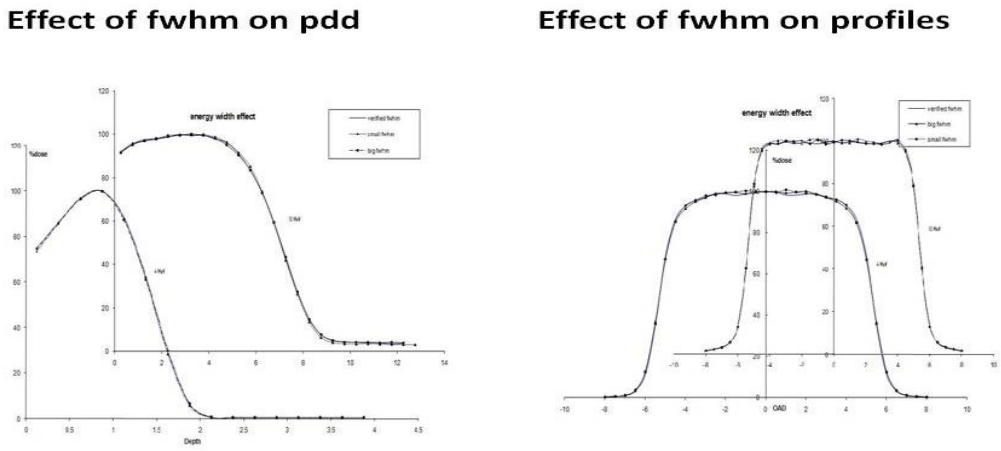

Fig. 1: Effect of alterations of the energy width on pdd and profiles

3.2 Source-To-Surface Distance (SSD): From Figure 2 below it is evident that increasing the SSD from 95 cm to 105 cm slightly reduced the surface dose with almost no effect in the remaining parts of the PDD. This is basically because the difference in distance from the source is not big enough to cause the effect of the inverse square law for distances. The big

effect is witnessed on the dose profiles, where the penumbra increases drastically with increase in SSD, as a result of the air gap.

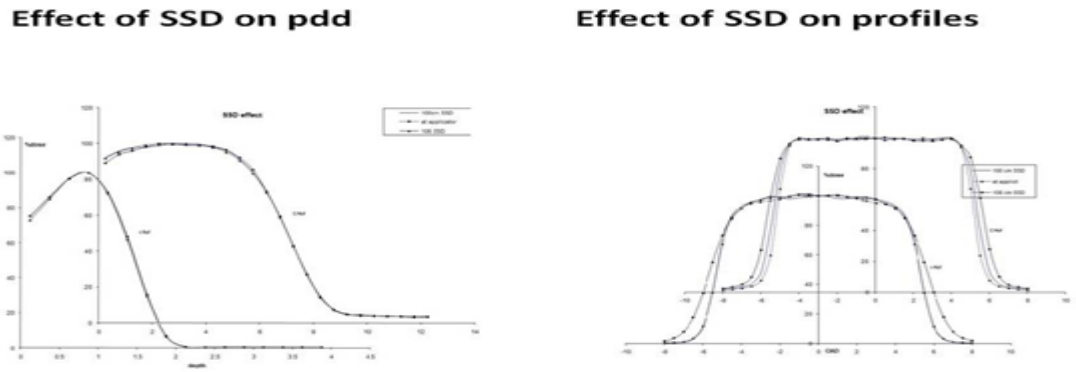

Fig. 2: Effect of alterations of the source-to-surface distance on pdd and profiles

3.3 Voxel Size: Figure 3 below demonstrates the effect of voxel size on both PDD and dose profiles. It was determined that using small voxel dimensions affect the surface dose. A difference of more than 10% is realised between the small voxel size and the medium or big voxel sizes. The effect on the profiles is more witnessed with big voxel sizes, where the shoulders become narrower and the penumbra much wider. With small voxels the profile is less flat and the percentage error of the highest doses is much larger than the other values. The maximum error of the highest doses exceeds 1% only with small voxels.

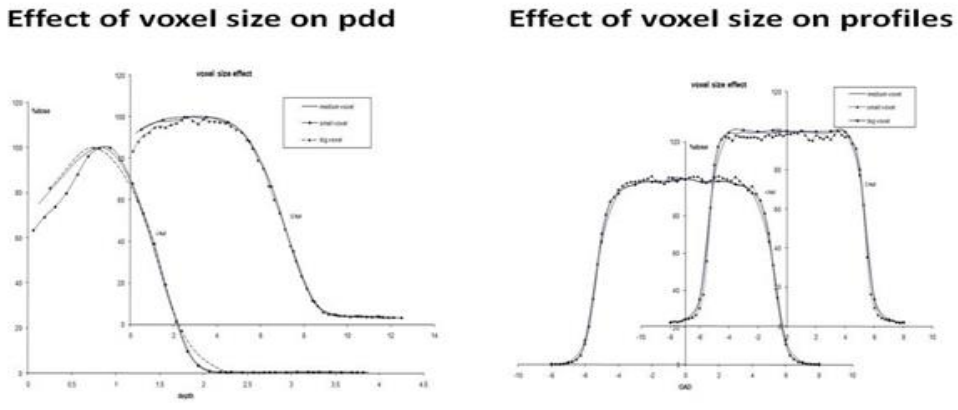

Fig. 3: Effect of alterations of the size of voxels on pdd and profiles

3.4 The Scattering Foils: The presence of the walls of the secondary scattering foils affect both PDDs and beam profiles. More effect is noticed on the PDD of the high energy (18 MeV). Dmax and the whole fall-off region are shifted towards the surface and the dose

gradient is slightly increased when the walls were simulated using FLATFILT component module. The walls improve the flatness of the profiles, especially at the shoulder region. No effect is seen on the penumbra. This is illustrated in Figure 4 below

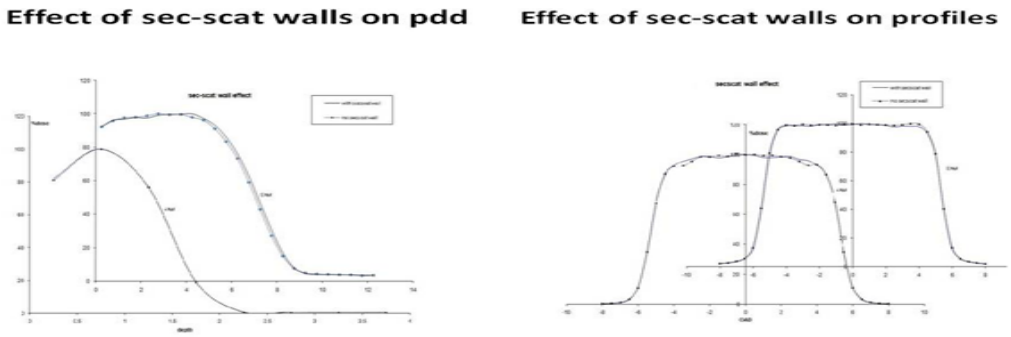

Fig. 4: Effect of the secondary scattering foil walls on pdd and profiles

3.5 The Ionization Chambers: Little effect is seen on the PDD when simulating the Linac without the ionization chamber or when altering the thickness of its walls or when simulating it using CONSTAK rather than IONCHAMB CM for all energies. A big different though is noticed when simulating it using SLAB, especially for the low energy (4 MeV) beam. The whole fall-off region is shifted towards the centre and the dose gradient is slightly decreased. Regarding the dose profiles, a slightly higher dose is noticed around the central axis when simulating the Linac without the ionization chamber. SLAB option also causes depression of the profiles at the shoulder region. Less effect is noticed as the energy of the beam increases. The effect of alteration of the ionization chamber is illustrated in Figure 5 below for 4 MeV and 18 MeV.

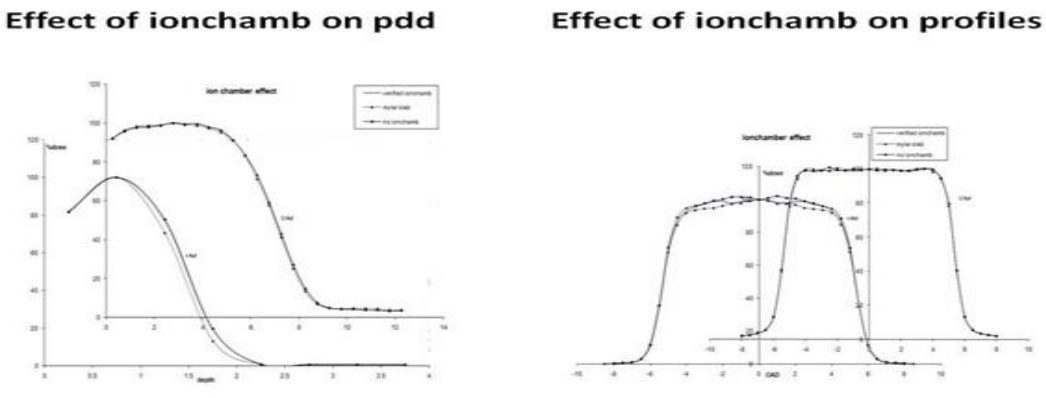

Fig. 5: Effect of alterations of the ionization chamber design on pdd and profiles

3.6 The Mirror: The presence of the mirror does not affect high energy beams. It slightly reduced the surface dose of the PDDs for low energy beams without affecting the dose

gradient. A slight depression in the shoulder region of the profile of the low energy beams is noticed when the Linac is simulated without the mirrors. No effect is realized on the penumbra as the result of absence of the mirror. Figure 6 below illustrates the effects of the mirror on the PDD and dose profiles for 4 MeV and 18 MeV.

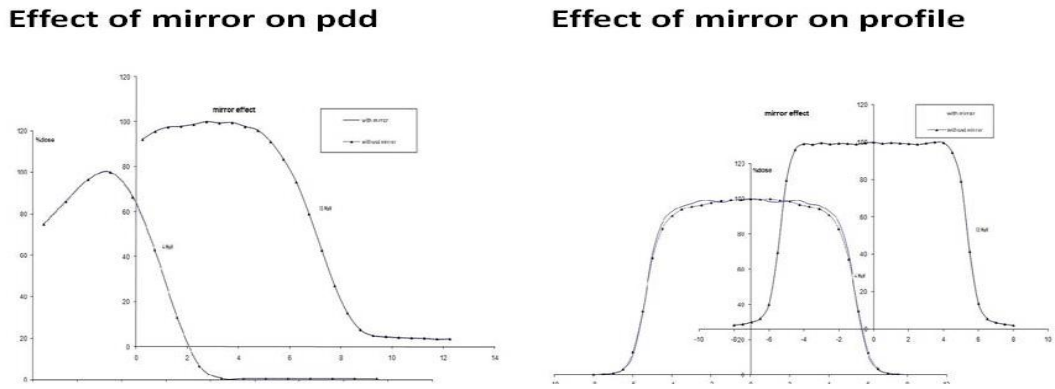

Fig. 6: Effect of the mirror on pdd and profiles

3.7 The Jaws: The jaws opening obtained from the Linac monitor, referred to as monitor jaws slightly underestimates the surface dose of the PDD for low energy beams. No effect is noticed for higher energies, or in the fall-off region or Bremsstrahlung tail of any of the energies. More effect is realised on the dose profiles where "horns" are produced with the monitor jaws openings. The effects of the jaws opening is illustrated in Figure 7 below.

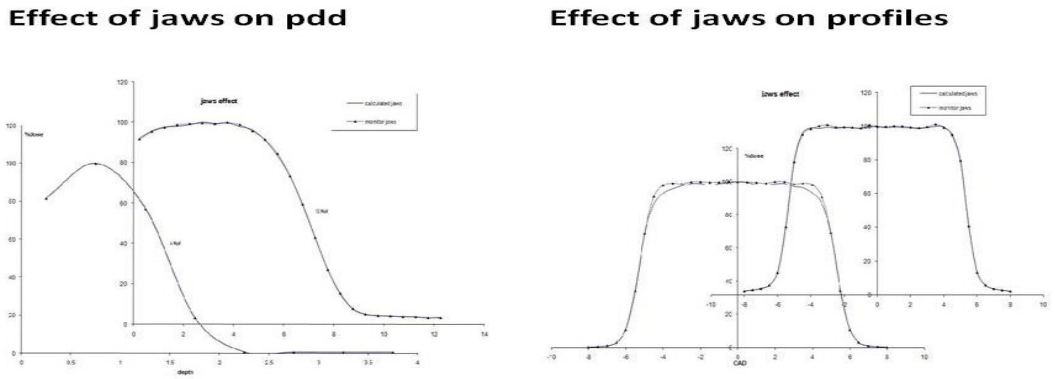

Fig. 7: Effect of alterations of the jaws opening on pdd and profiles

3.8 The Applicators: The effect of the applicator materials is very evident for high energy electron beams as seen on Figure 8 below. Using Aluminum applicators completely deforms the PDD by reducing the "plateau" of uniform dose and decreases the dose gradient. It also affects the dose profiles by reducing the dose near the central axis and increases the dose at the edges. Less effect is seen for the low (4 MeV) beam.

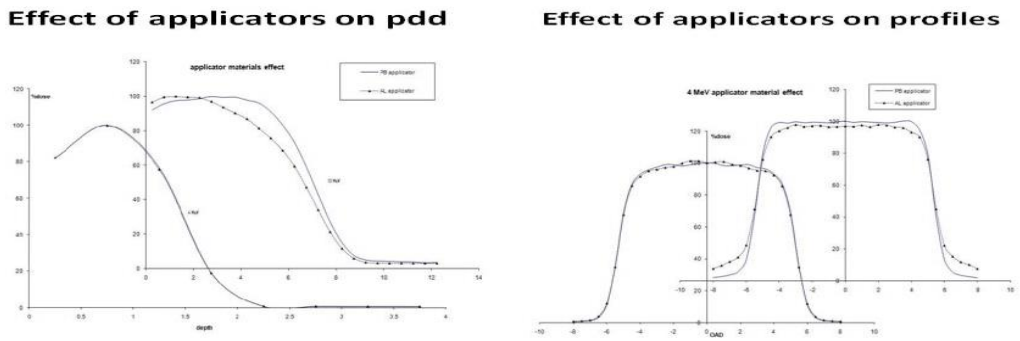

Fig. 8: Effect of applicator materials on pdd and profiles

4. DISCUSSION:

Accurate simulation of the beam parameters and linear accelerator configurations is very crucial for electron beams since slight alterations may affect the output dose distribution. This paper studies some of the effects caused by slight alterations on both percent depth dose and lateral dose profiles as summarized below.

4.1 Energy Distribution of The Initial Beam: The energy width of the electron beam that produces a good match between measured and calculated PDDs and dose profiles ranges from 20% to 30% of the most probable energy, depending on the energy. The percentage is higher for lower electron beam energies. An increase in this value affects the flatness of the beam profiles and a decrease may increase the dose gradient resulting in miss-match between the measurements and calculations.

4.2 Source to Surface Distance (SSD): When electrons are simulated for clinical applications the actual SSD should be accounted for because slight alterations were found to influence the surface dose as well as the lateral dose distributions.

4.3 Voxel Size: Voxel sizes of 0.5x0.5x0.5 cm^3 seem to give a better match between measured and calculated data. Decreasing the voxel size increases the uncertainty because fewer particles deposit dose in a small volume. Increasing the voxel size reduces the uncertainty but may introduce errors due to reduced spatial resolution. This is seen clearly in the results where the dose at the edges was not accurately measured.

4.4 The Secondary Scattering Foils: FLATFILT component module is recommended for simulating the secondary scattering foils because it allows simulating the foils for different energies and includes the walls. The walls of the secondary scattering foils were found to influence the dose distributions especially for higher energies electron beams, were walls can be simulated with FLATFILT.

4.5 The Ionization Chambers: Although IONCHAMB component module does not account for the difference in the materials of the inner walls, it allows accurate simulation of the ionization chambers as shown in the results. The segmentation of the ionization chamber reduces scatter effects [21]. This is probably why simulating the ionisation chamber as a SLAB of Mylar had more influence on the PDD than not simulating it at all. Absence of this component module did not have a big influence on the PDD but reduced the flatness of the beam profiles.

4.6 The Mirrors: It is necessary to accurately simulate the mirrors for low energy electron beams because despite its thin nature, it can affect the scattering of the low energy beams. Mirrors do not affect the moderate or high energy beams.

4.7 The Jaws: The jaws opening values obtained from the Linac monitor, referred to as monitor jaws are bigger than the calculated openings, especially for 4 MeV. This results in more scattered radiation at the edges of the beam. It is thus necessary to calculate the jaws openings according to the required field size.

4.8 The Applicators: The applicators play the most important role in beam shaping and have a major role in dose distribution due to their scattering effects on the electron beams at the water phantom. The amount of scattered radiation from applicators is dependent on the applicator design and materials. Applicators made from high Z materials such as lead are the ones of choice especially when dealing with high electron energies. Low Z materials such as aluminum can be used only for low energy electron beams.

5. CONCLUSIONS:

Accurate simulation of the linear accelerators is crucial for proper Monte Carlo calculations of beam distributions in patients. This work shows the necessity of the accuracy of simulating some of the beam parameters, the water phantom and the different Linac configurations and explains systematic errors that arise from slight alterations in these values. Percent depth dose curves are more influenced by accurate modelling of the different parts of the linear accelerator, especially the scattering foils, the monitor ionization chambers and the applicator materials. Beam parameters, source-to-surface distance, voxel sizes as well as some Linac components such as scattering foil walls, jaws opening and material of the applicators affect the off-axis dose distributions especially in the plateau and the shoulder regions.

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