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Monte Carlo Investigation of Inhomogeneity Phantom Effects in 6 MV Photon Beam

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ABSTRACT.
The objective of this study is to investigate the inhomogeneity effect in inhomogeneous phantom using dosimetric parameters which are the percentage depth dose (PDD) and lateral profile. The accelerator treatment head used in this study was Varian Trilogy Clinac iX 6 MV photon beam. BEAMnrc Monte Carlo (MC) code system was used to design this linear accelerator (linac) based on manufacturer's details information. The resulting phase space scoring plane after multi-leaf collimator (MLC) component form BEAMnrc was used as an input for the DOSXYZnrc code, which gives the dose distributions of the inhomogeneous phantom. The inhomogeneous phantom consists of solid water (Sun Nuclear) and styrofoam material with varied thickness of 1, 2 and 3 cm. The PDD and lateral profile resulted from MC simulation and measurement data from Tan Tock Seng Hospital Singapore was compared for field size 5×5 and 10×10 cm^2. The results show that the PDD and lateral profile trends are similar. However, there is a discrepancy of approximately 4% between measured and predicted values which can be associated with the field angle and the degree of inhomogeniety.

Introduction

The human body consists of a variety of tissues with different physical and material properties (water, lung, bones, etc). The density of each material is varied too. Every material has different radiation dosimetry perspective. Study of inhomogeneity effect in human body have been conducted from many researchers (Sterpin *et al*., 2007; Don Robinson, 2008; Chow *et al*,. 2009; Cardoso *et al*., 2010; Ham *et al*., 2011; Chandola *et al*., 201; Nedaie *et al*., 2013; Lloyd and Ansbacher, 2013). Inhomogeneous organ such as lung is more challenging in radiotherapy calculation of dose distribution. The inhomogeneity effect can affect the accuracy of the dose distribution as well as the benefit of radiotherapy and patient survival.

Nowadays, Monte Carlo techniques become gold standard in medical physics to simulate electron and photon transport in materials especially to calculate dose distribution in inhomogeneous phantom. MC code used in medical physics were Geant4, MCNP (Nedaie *et al*., 2013), EGSnrc (Chow *et al*., 2009), EGS4, etc. Nedaie *et al.* (2012) found the good agreement of dose distribution of measurement data and MCNP4C results in a homogenous and inhomogenous phantom. MC algorithm becomes most popular method to investigate the effect of inhomogeneity (Chow *et al*., 2009; Chandola *et al*., 2011).

The objective of this study is to investigate the inhomogeneity effect in inhomogeneous phantom (solid water – styrofoam – solid water) using dosimetric parameters (the central axis percentage depth dose (PDD) and beam profiles at specific depth) using EGSnrc Monte Carlo code system. The measurement data from hospital will be compared with MC data to validate the results.

Materials and methods

Accelerator

The accelerator treatment head was used in in this study type Varian Trilogy Clinac iX (Varian Oncology Systems, Palo Alto, CA 94304 USA). This accelerator has a standing waveguide and a 270° bending magnet. Photon beam modalities 6 MV were investigated (Figure 1).

Figure 1. Varian Trilogy Clinac iX 10 MV photon beam (source: Tan Tock Seng Hospital (TTSH) Singapore)

Phantom measurement

The phantom used in this study consisted of solid water (Sun Nuclear) and styrofoam material (Figure 2). The solid water made of water equivalent RW3 material with mass density 1.045 g/cm^3. Solid water consists of several different thicknesses (range from 0.1 cm to 1 cm). In this study, solid water with different thickness arranged to get the desired thickness. For example, 6 pieces of solid water with 1 cm thickness packed to get 6 cm of solid water. And the styrofoam material have mass density 0.035 g/cm^3. The lateral dose profile measurements were performed for two field sizes 5×5 and 10×10 cm^2 using IC profiler (Sun Nuclear) detector placed after styrofoam perpendicular to the beam axis. The IC profiler has 139 diode detectors with dimension 2.9 mm. The dose distribution data obtained from IC profiled was stored in a .rpm file and proceed by Microsoft excel. This data contain the dose in each detector (X, Y, PD and ND direction) (Figure 3). The dose were normalized to maximum dose.

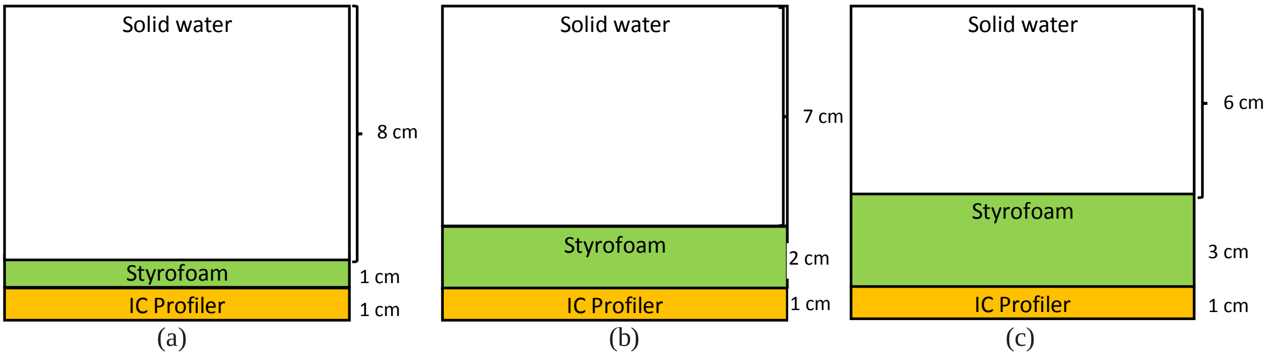
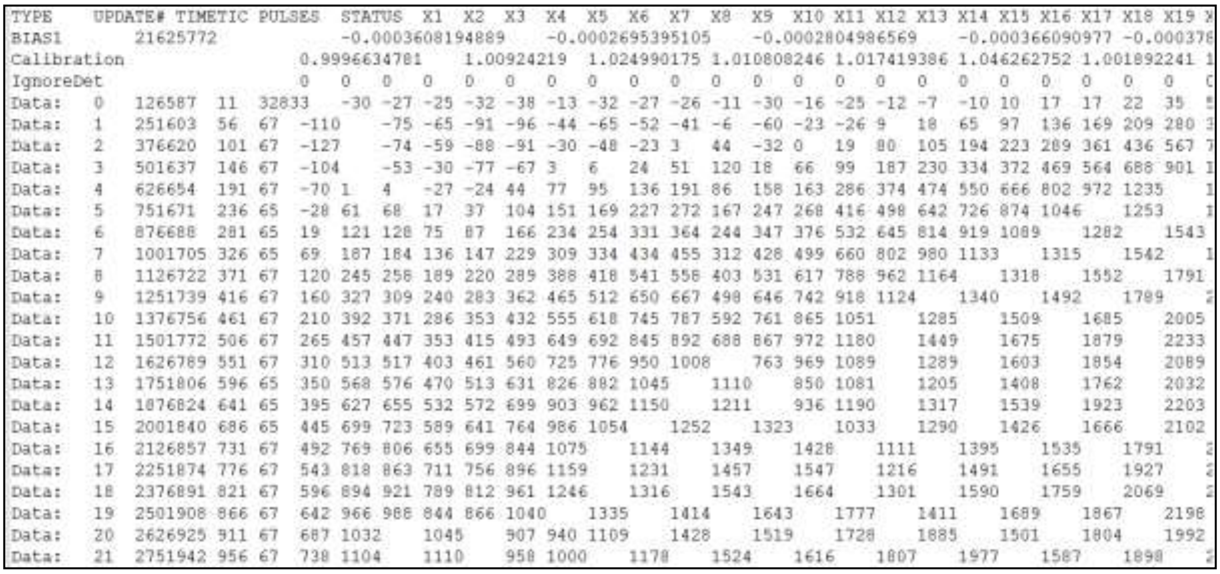


Figure 2. Inhomogeneous phantom with various thickness of styrofoam (a) 1 cm (b) 2 cm (c) 3 cm



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Data:	4	626654	191	67	-70	1	4	-27	-24	44	77	95	136	191	86	158	163	286	374	474	550	666	802	972	1235
Data:	5	751671	236	65	-28	61	68	17	37	104	151	169	227	272	167	247	268	416	498	642	726	874	1046	1253
Data:	6	876688	281	65	19	121	128	75	87	166	234	254	331	364	244	347	376	532	645	814	919	1089	1282	1543
Data:	7	1001705	326	65	69	187	184	136	147	229	309	334	434	455	312	428	499	660	802	980	1133	1315	1542
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Data:	10	1376756	461	67	210	392	371	286	353	432	555	618	745	787	592	761	865	1051	1285	1509	1685	2005
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Data:	13	1751806	596	65	350	568	576	470	513	631	826	882	1045	1110	850	1081	1205	1408	1762	2032
Data:	14	1876824	641	65	395	627	655	532	572	699	903	962	1150	1211	936	1190	1317	1539	1923	2203
Data:	15	2001840	686	65	445	699	723	589	641	764	986	1054	1252	1323	1033	1290	1426	1666	2102
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Figure 3. Dose distribution data obtained from IC profiler and stored in .rpm file

Monte Carlo modelling of Varian Trilogy Clinac iX 6 MV photon beam

The EGSnrc MC code is currently used to model lineac accelerator (linac) and calculate dose distribution in inhomogeneous phantom developed by the National Research Council of Canada (Kawrakow and Rogers, 2011). EGSnrc has 2 main derived code used to spesific purpose, e.g. BEAMnrc and DOSXYZnrc. BEAMnrc code system used to design a linac based on manufacturer's detailed information (material and geometry spesification of each linac components) (Rogers *et al.*, 2011). Main output of this code is the phase space (phsp) distributions contain the particle information released from linac. The components of a linear accelerator for 6 MV photon beams was shown in Figure 4. ECUT 0.521 MeV and PCUT 0.01 MeV were chosen in this study. The initial electron energy and FWHM of source were 6.4 MeV and 0.1 mm, respectively besed on commissioning process from our previous study (Dirgayussa *et al.*, 2015). The spectra distribution from phsp file was obtained using BEAMDP (BEAM data processor) showed in figure 5.

TRANSACTIONS ON SCIENCE AND TECHNOLOGY

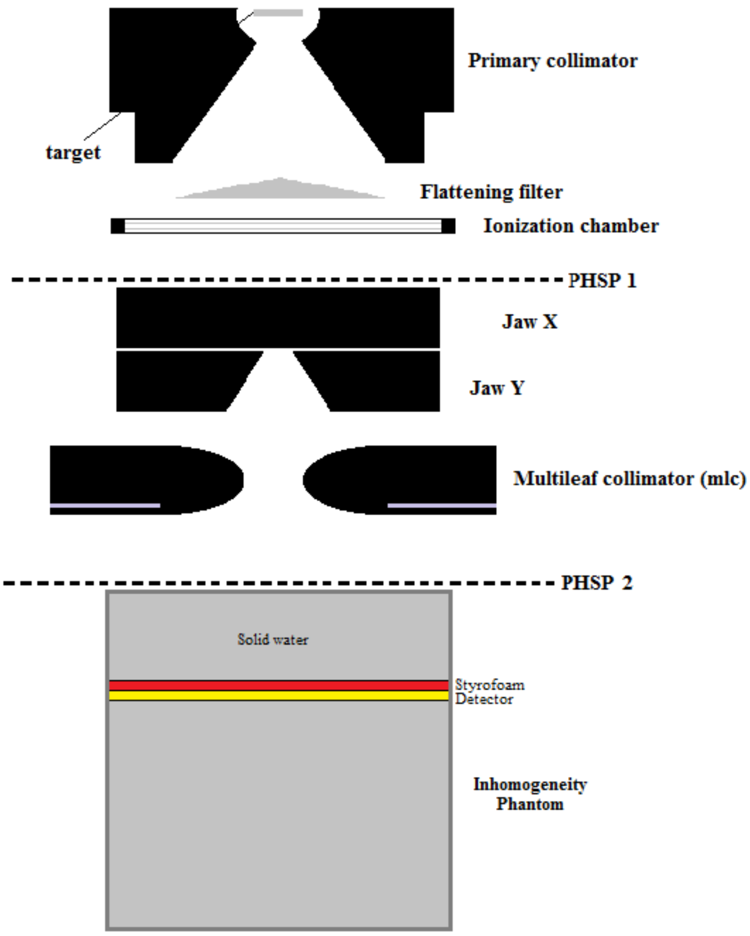

Figure 4. Schematic diagram of Varian Trilogy Clinac iX 6 MV photon beam treatment head

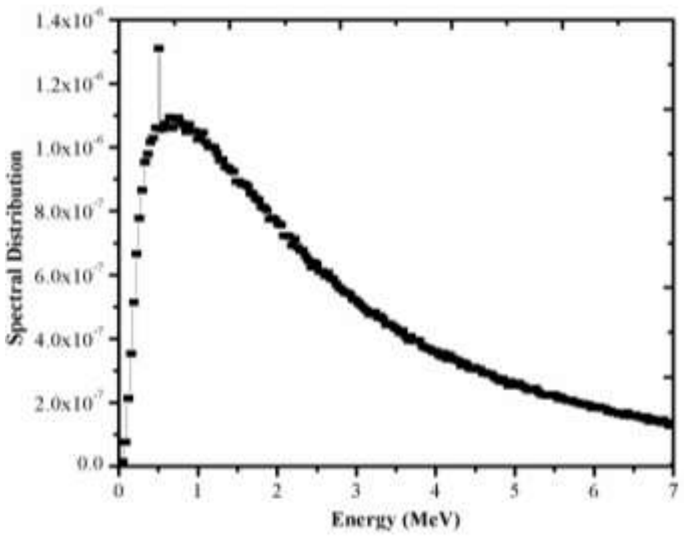

Figure 5. Spectral distribution of all particle (defined at the phsp file (80 cm from target) and incident electron energy 6.4 MeV) inside the field size 10×10cm^2

The resulting phase space scoring plane after mlc component was used as an input for the DOSXYZnrc code, which calculates the dose distributions in a phantom (Walters *et al*., 2011). The voxel size for PDD and lateral profile were distiguished to get the best resolution and the shortest simulation time (Yani *et al*., 2015). To get the minimum statistical uncertainty, the number of history was used 1×10^{9} particles. Solid water and styrofoam cross section data was created using EGSnrc program by provide the informations of material composition (element, mass density, and fraction by weight) each it. The dose distribution data obtained from DOSXYZnrc was stored in a .3ddose file and proceeds by STATDOSE to get the PDD and lateral profile data. The .3ddose file contains number of voxel (volume element), position of voxel, dose value in each voxel and error value (Figure 6).

```
        3           3          54
 -20.000000   -1.5000000    1.5000000    20.000000
 -20.000000   -1.5000000    1.5000000    20.000000
  0.0000000   0.40000001   0.80000001    1.0000000    1.2000000    1.4000001    1.6000001    1.
  2.0000002    2.2000003    2.4000003    2.6000004    2.8000004    3.0000005    3.2000005    3.
  3.6000006    3.8000007    4.0000005    5.0000005    6.0000005    7.0000005    8.0000000    9.
  10.000000    11.000000    12.000000    13.000000    14.000000    15.000000    16.000000    17
  18.000000    19.000000    20.000000    21.000000    22.000000    23.000000    24.000000    25
  26.000000    27.000000    28.000000    29.000000    30.000000    31.000000    32.000000    33
  34.000000    35.000000    36.000000    37.000000    38.000000    39.000000    40.000000
1.0450216215979326OE-017  3.9153798070438434 7E-017  1.1821279812849482 7E-017  3.2611572096107612 5E-017  1.921897645
5.5628031823798983 5E-017  1.7550006990327700 4E-017  1.3003194809712552 9E-017   5.0992808108101931 1E-017  1.183407
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1.1470176000715242 8E-017  4.8924025281566037 8E-017  1.2110864889243831 2E-017  1.1679175260155291 8E-017  5.055498468
2.4853422575407691 8E-016  4.6717738298456373 6E-017  1.1472580998136262 3E-017  4.8572548271168668 8E-017  1.20830231
```

Figure 6. Dose distribution data obtained from DOSXYZnrc and stored in .3ddose file

Result and discussion

The lateral profile curves along the central axis provided from Monte Carlo simulation data were compared to measurements data for 6 MV photon beam, field size 5×5 and 10×10 cm^2 and SSD 100 cm (Figure 7).

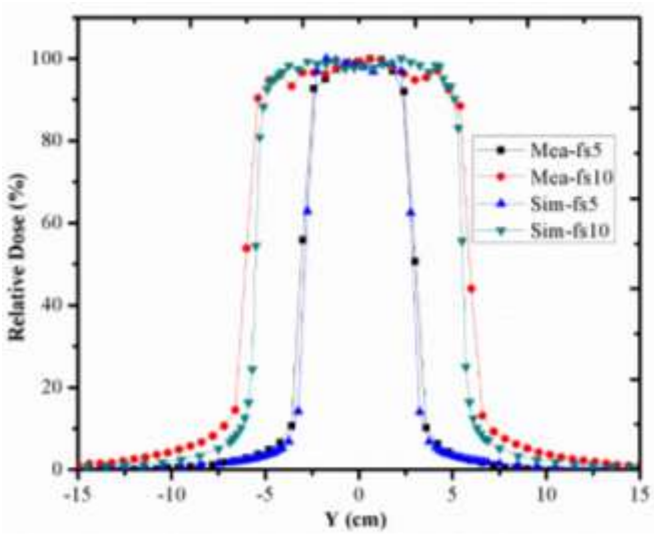

Figure 7. Comparison of lateral profile between measurement and Monte Carlo simulation for field size 5×5 (black and blue lines) and 10×10 cm^2 (red and green lines). (Mea=measurement data and Sim=simulation data)

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The reference data were obtained to verify the field size using solid water. This lateral profile scored at depth 10 cm and normalized with the dose maximum measured. The profile trends are similar for the measured and Monte Carlo results, but there is an offset approximately 5% between measured and computed data. The physical penumbra widths (20% - 80%) calculated by Monte Carlo agree well with those of the measurement data with differences less than 1 cm. The penumbra widths of the 10×10 cm^2 are larger than 5×5 cm^2 field. This discrepancy is attributed to the actual density of styrofoam and size of detector used in measurements. Computer run times were 4.7 hours by i5 computer with 4 cores. There is no large statistical uncertainty founded in this simulation. This figure shows the dose variation across the defined field at a 10 cm depth. In addition, the beam profile shows the beam flatness and the defined field size showing that the dose is uniform across the 5×5 and 10×10 cm^2 field. Thus, these results are used to validate the correct geometry for the flattening filter and collimated jaws simultaneously.

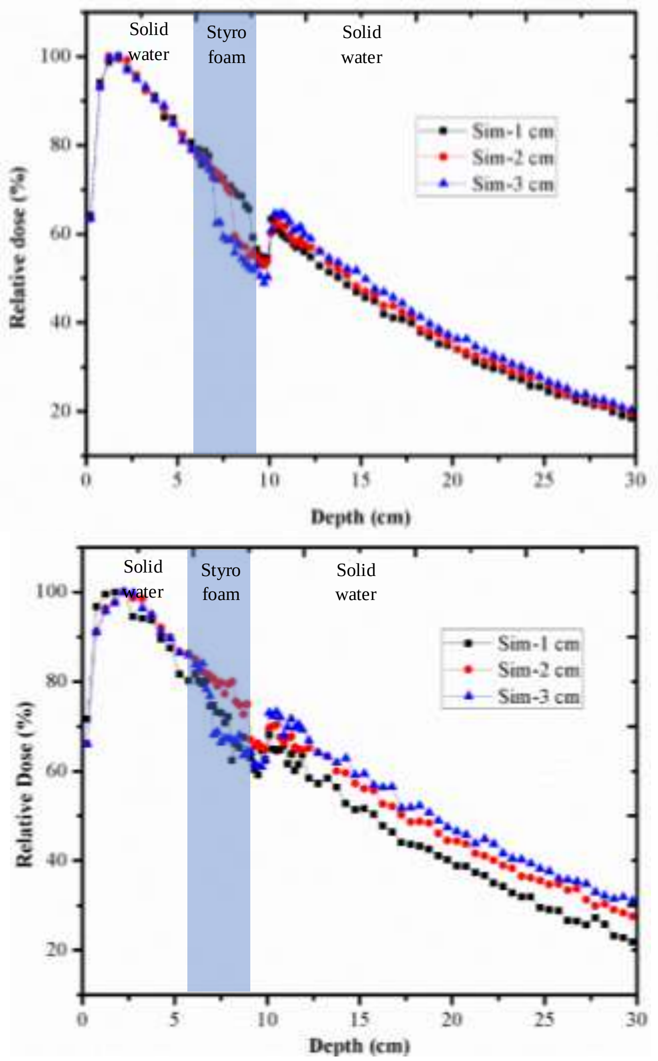


Figure 8. Comparison PDD obtained from Monte Carlo calculation for 6 MV X-ray fields of various styrofoam thickness for field size (a) 5×5 and (b) 10×10 cm^2. The black, red and blue lines are 1, 2 and 3 cm of styrofoam thickness obtained by Monte Carlo calculation.

It can be seen from Figure 8 that the boundaries between inhomogeneities were clearly visible. The absorbed dose is reduced dramatically in styrofoam material for both field sizes (5×5 and 10×10 cm^2) and styrofoam thickness (1, 2 and 3 cm). The dose was fall-off in the boundary between solid water and styrofoam and then increased in the boundary between styrofoam and solid water. There was not shift Dmax for each styrofoam thickness. For field size 5×5 cm^2, the amount of dose reduction in styrofoam was 13%, 18% and 24% for styrofoam thickness 1, 2 and 3 cm, respectively. For field size 10×10 cm2, the amount of dose reduction in styrofoam was 10%, 7% and 15% for styrofoam thickness 1, 2 and 3 cm, respectively. The styrofoam density is lower than solid water density. When photon with certain energy passed low density material, most of them will be transmitted. So, the absorbed energy in this region will decrease. Some of photons will be transmitted to the next material (solid water). These photons affect the increasing of absorbed dose in solid water region. Several studies have reported underdosing at interfaces due to loss of electronic equilibrium. Chow *et al.* (2009) compared the PDD and lateral profile in a slab phantom contains water and lung slab. The mass density of lung slab is varied with 0.05, 0.08, 0.1, 0.3, 0.5, and 0.7. The results show that the decrease in the mass density of lung caused a decrease in photon attenuation and an increase in depth dose (Figure 9).

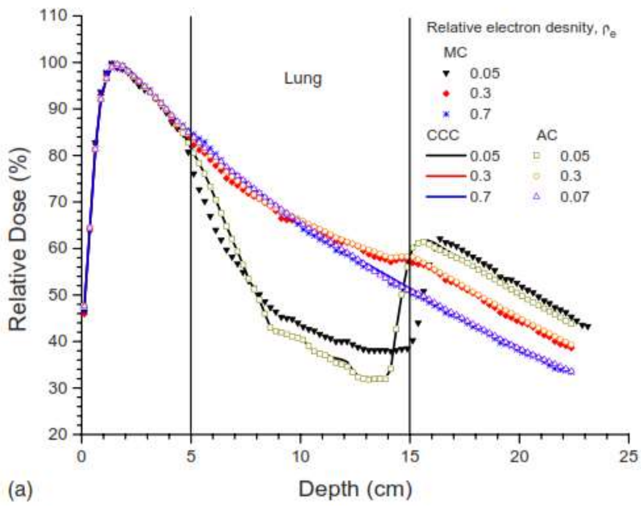
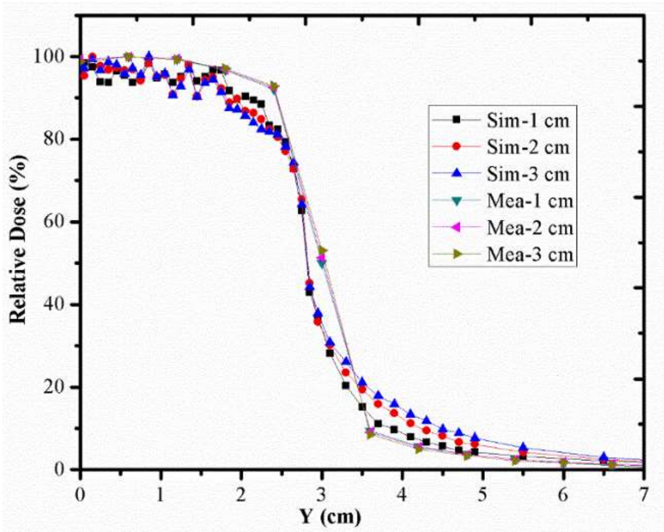


Figure 9. PDD of the slab phantom for a 6 MV photon beam with field size of 4×4 cm^2. The PDD was normalized to the dose at D_{max} in a reference water phantom (Chow *et al*., 2009)

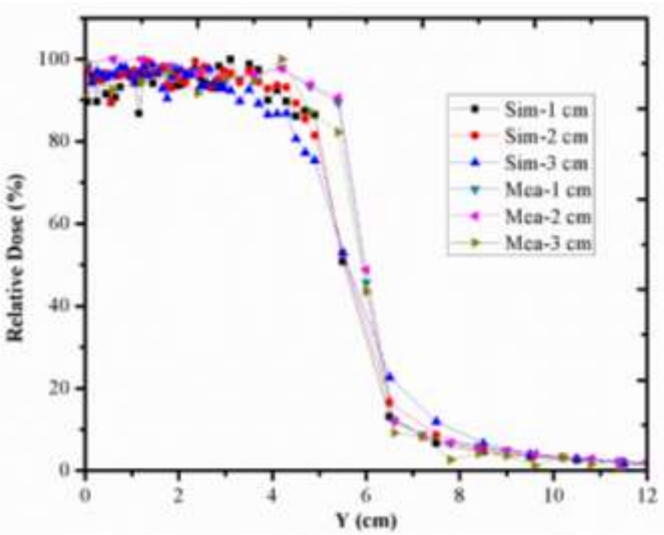
From figure 10 shows that the curve trends are similar for the measurement and Monte Carlo results, but there is a discrepancy approximately 4% between measured and computed data for both 5×5 and 10×10 cm^2 and styrofoam thickness. The lateral profiles were measured at 10 cm depth. Indeed, there is a small reduction in dose attributable to decreased backscatter from the low-density region. The field size was 10 cm in diameter, which is large enough to establish lateral electron equilibrium at the central axis. Therefore, the reduction of dose could not have been due to lack of lateral equilibrium. Lateral disequilibrium of electrons can produce perturbations in dose in low-density regions in inhomogeneous phantoms. For field size 5×5 cm^2, the FWHM (Full Width at Half

Maximum) was 5.5 and 6 cm for Monte Carlo and measurement data, respectively. And for field size 10×10 cm^2, the FWHM was 11 and 11.6 cm for Monte Carlo and measurement data, respectively.

The penumbra broadening of a photon beam becomes one of mayor factor to concern with especially in inhomogeneous phantom. For field size 5×5 cm^2, the physical penumbra width (an area where the dose reduced significantly between 20% and 80%) was 0.9 and 1.3 cm for Monte Carlo and measurement data, respectively. And for field size 10×10 cm^2, the physical penumbra width was 2 and 1.5 cm for Monte Carlo and measurement data, respectively (Figure 10).



(a)



(b)

Figure 10. Comparison lateral profile obtained from Monte Carlo calculation for 6 MV X-ray fields of various styrofoam thickness for field size (a) 5×5 and (b) 10×10 cm^2. (Mea=measurement data Sim=simulation data)

Lateral profile cannot directly express the effect of inhomogeneity in a phantom with field size 5×5 and 10×10 cm^2 both simulation and measurement results even though the thickness of styrofoam varied. But, this effect can show clearly in PDD curve. The material boundaries with different density was clearly visible especially for field size 5×5 cm^2 (Figure 9 and 10).

Conclusion

Monte Carlo based dose calculations for Varian Trilogy Clinac iX photon beam linear accelerator electron in inhomogeneity phantom (solid water – styrofoam – solid water) have been demonstrated to be accurate at the 4% level in comparison with measurements. The PDD can express the effect of inhomogeneity clearly in a phantom with field size 5×5 and 10×10 cm^2 both simulation and measurement results with the thickness of styrofoam varied.

Acknowledgements

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References

[1] Cardoso, S. C., Alves, V. G. L., da Rosa, L. A. R., Campos, L. T., Batista, D. V. S. & Facure, A. (2010). Monte Carlo Simulation of Bony Heterogeneity Effects on Dose Profile for Small Irradiation Field in Radiotherapy. *Plos One*, **5**(5), e10466.

[2] Chandola, R. M., Tiwari, S., Painuly, N. K., Choudhary, V., Azad, S. K. & Beck, M. (2011). Monte Carlo Study of Dosimetric Parameters and Dose Distribution Effect of Inhomogeneities and Source Position of GammaMed Plus Source. *Journal of Cancer Research and Therapeutics*, **7**(1), 29-34.

[3] Chow, J. C. L., Leung, M. K. K. & Dyk, J. V. (2009). Variations of Lung Density and Geometry on Inhomogeneity Correction Algorithms: A Monte Carlo Dosimetric Evaluation. *Medical Physics*, **36**(8), 3619-30.

[4] Dirgayussa, I. G. E., Yani, S., Rhani, M. F. & Haryanto, F. (2015). Commissioning process of Varian Clinac iX 6 MV photon beam. *AIP Conference Proceedings*, **1677**, 040006.

[5] Han, T., Mikell, J. K., Salehpour, M. & Mourtada, F. (2011). Dosimetric Comparison of Acuros XB Deterministic Radiation Transport Method with Monte Carlo and Model-based Convolution Methods in Heterogeneous Media. *Medical Physics*, **38**(5), 2651-64.

[6] Kawrakow, I. & Rogers, D. W. O. (2011). *The EGSnrc Code System: Monte Carlo Simulation of Electron and Photon Transport*. Ottawa: National Research Council of Canada

[7] Lloyd, S. A. M. & Ansbacher, W. (2013). Evaluation of an Analytic Linear Boltzmann Transport Equation Solver for High-density Inhomogeneities. *Medical Physics*, **40**(1), 011707-1-5.

[8] Nedaie, H. A., Mosleh-Shirazi, M. A. & Allahverdi, M. (2013). Monte Carlo N Particle Code - Dose Distribution of Clinical Electron Beams in Inhomogeneous Phantoms. *Journal of Medical Physics*, **38**(1), 15-21.

[9] Robinson, D. (2008). Inhomogeneity Correction and The Analytic Anisotropic Algorithm. *Journal of Applied Clinical Medical Physics*, **9**(2), 1-11.

[10] Rogers, D.W.O., Walters, B. & Kawrakow, I. (2011). *BEAMnrc Users Manual*. Ottawa: National Research Council of Canada.

[11] Sterpin, E., Tomsej, M., Smedt, B. D., Reynaert, N. & Vynckier, S. (2007). Monte Carlo Evaluation of The AAA Treatment Planning Algorithm in A Heterogeneous Multilayer Phantom and IMRT Clinical Treatments for An Elekta SL25 Linear Accelerator. *Medical Physics*, **34**(5), 1665-77.

[12] Walters, B., Kawrakow, I. and Rogers, D.W.O. (2011). *DOSXYZnrc Users Manual*. Ottawa: National Research Council of Canada.

[13] Yani, S., Dirgayussa, I. G. E., Rhani, M. F., Haryanto, F. & Arif, I. (2015). The Effect of Voxel Size on Dose Distribution in Varian Clinac iX 6 MV Photon Beam using Monte Carlo Simulation. *AIP Conference Proceedings*, 1677, 040002.