Inhomogeneity effect in Varian Trilogy Clinac iX 10 MV photon beam using EGSnrc and Geant4 code system

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Abstract. Treatment fields consist of tissue other than water equivalent tissue (soft tissue, bones, lungs, etc.). The inhomogeneity effect can be investigated by Monte Carlo (MC) simulation. MC simulation of the radiation transport in an absorbing medium is the most accurate method for dose calculation in radiotherapy. The aim of this work is to evaluate the effect of inhomogeneity phantom on dose calculations in photon beam radiotherapy obtained by different MC codes. MC code system EGSnrc and Geant4 was used in this study. Inhomogeneity phantom dimension is 39.5×30.5×30 cm3 and made of 4 material slices (12.5 cm water, 10 cm aluminium, 5 cm lung and 12.5 cm water). Simulations were performed for field size 4×4 cm2 at SSD 100 cm. The spectrum distribution Varian Trilogy Clinac iX 10 MV was used. Percent depth dose (PDD) and dose profile was investigated in this research. The effects of inhomogeneities on radiation dose distributions depend on the amount, density and atomic number of the inhomogeneity, as well as on the quality of the photon beam. Good agreement between dose distribution from EGSnrc and Geant4 code system in inhomogeneity phantom was observed, with dose differences around 5% and 7% for depth doses and dose profiles.

1. Introduction
The accuracy of dose calculation in the treatment planning is important to ensure the appropriate dose delivered to patients undergoing radiation therapy. In the past 20 years, radiation therapy has become increasingly thrive. Uncertainty in dose calculation is very challenging today. Many researchers develop methods to reduce this in order to inhomogeneity inside treatment fields. This treatment fields consist of tissue other than water equivalent tissue (soft tissue, bones, lung etc). Where the tissue is not water, equivalent distortions to the beam profiles will occur. If the density is substantially less than that of water, as in lung or in air cavities, the attenuation will be reduced. Photon dose distribution using analytical methods are associated with large uncertainties, especially in irradiated volumes that contain inhomogeneity such as air cavities and bones. In clinically relevant dose calculations, errors of 10% or greater have been reported to be associated with analytic dose calculation methods.

Monte Carlo (MC) techniques are becoming more widely used in all medical physics applications. MC simulation of radiation transport is one of the most accurate methods for predicting absorbed dose
distributions in radiation therapy. The MC method is the most accurate method for dose calculation in photon beams and can potentially reduce these uncertainties to a few percent. MC algorithm would be acceptable for determining the absorbed dose in the presence of inhomogeneous tissue if the Monte Carlo code is tested sufficiently. In particular, MC simulation can handle backscatter from high-density materials (such as aluminium) or scatter perturbations by low density material (such as lung) more accurately than any other current dose calculation method. Some studies have been conducted to investigate inhomogeneity effect using Monte Carlo simulation for external beam radiation therapy (EBRT) [1, 2] and brachytherapy [3, 4].

There are different MC codes for the simulation of photons, electrons and the coupled transport of electrons and photons e.g. MCNPX, Electron Gamma Shower (EGS) and Geant4. These code generally used in medical physics application [5, 6, 7]. Both of EGSnrc and Geant4 were used to model and simulate particle transport and interaction with matter across a wide range of energies using MC algorithm. Geant4 is a Monte Carlo-based code that is a successor of GEANT3 developed in two independent studies at CERN and KEK in 1993 [6]. This code have a wide range energy than EGSnrc code.

![Figure 1. Varian Trilogy Clinac iX linear accelerator (source: Tan Tock Seng Hospital (TTSH) Singapore).](source)

The aim of this study is to evaluate the effect of inhomogeneity phantom on dose calculations in Varian Trilogy Clinac iX 10 MV photon beam (figure 1) obtained by Geant4 and EGSnrc code system. Neutron can be emitted from high energy linear accelerator. For this study of inhomogeneity phantom on dose distribution used Geant4 code system to detect the existence of these particles.

2. Methods

Monte Carlo simulations were performed using Geant4 [8] and DOSXYZnrc the user code of EGSnrc [9]. These codes use three-dimensional heterogeneous geometry and transports photons and electrons in the energy range from 1 KeV to some GeV. But, one of the limitation of EGSnrc is in order to calculate the neutron contamination and interaction in a simulation. The accelerator employed was a Varian Trilogy Clinac iX Varian Oncology Systems, Palo Alto, CA with the available nominal energies of 4, 6, 8, 10, 15, 18, and 20 MeV for photon beam. In this study we performed dosimetric verifications of the treatment planning system limited to 10 MeV photon beam. The dose profiles
curves and percent depth doses curves from Geant4 and EGSnrc were compared both of homogeneous and inhomogeneous phantom.

2.1. Homogeneous phantom
A water phantom was used as a homogenous phantom for relative dosimetry. The phantom was a cube of dimensions \(39.5\times30\times30\) cm\(^3\) were placed in the radiation field for scanning (figure 2a).

2.2. Inhomogeneous phantom
The phantom were made of 4 material slices (3 cm water, 2 cm aluminium as high density material, 7 cm lung as low density material and 18 cm water) (figure 2b). The materials chosen had linear collision stopping powers and linear angular scattering powers close to body tissues. The aluminum and lung material were chosen to represent high and low density material, respectively. Sometimes, some patients have implants in their body that consist of metal or another high density materials. Inhomogeneity phantom dimension is \(39.5\times30.5\times30\) cm\(^3\). This inhomogeneity phantom adopt from Jan et. al. (2011) [10].

![Figure 2. Phantom design (a) Homogenous phantom (b) Inhomogeneous phantom.](image)

Simulations were performed for a square field size 4×4 cm\(^2\) at a source-to-axis distance (SSD) of 120 cm. The source used in Geant4 and DOSXYZnrc simulation is point source from the front of rectangular collimation (source 3) using the spectrum distribution Varian Trilogy Clinac iX 10 MV photon beam from Tan Tock Seng Hospital (TTSH) Singapore (figure 3).

About \(10^9\) histories are traced here to perform the simulation for evaluation of the homogenous and inhomogeneous phantom on dose distribution. The scoring voxel arrangement for percentage depth dose (PDD) and profile dose calculation is different to reduce simulation time and concern on high dose gradient and build-up region [11]. This simulation takes about 12-14 hours to complete depend on voxel sizes and the number of computer core. MC simulated and measured dose distributions in a water phantom. The output of this simulation i.e. the percent depth dose and dose profile in \(d_{\text{m}}\). For the calculations in this study, the global cut-off energies used in the simulations were electron cut-off energy (ECUT) = 521 KeV for electrons and photons global cut-off (PCUT) = 10 KeV for photons. The dose distribution from this simulation was analyzed and plotted using a STATDOSE code. The number of histories was selected in order to get the desired statistical uncertainty (standard deviation) on the dose calculation of about less than 2%. 
3. Results and discussion

3.1. Homogeneous phantom

Figure 4 summarize the differences the calculated (simulated) dose in PDD and profile dose for field size 4×4 cm$^2$ and SSD 120 cm between Geant4 and EGSnrc code system. The discrepancies between measured and calculated dose data are within 5% of $D_{\text{max}}$ ($D_{\text{max}}$ is phantom depth with maximum dose). The dose profile simulate to verify the field size used in simulation in homogenous (water) phantom (figure 4). Dose profile scan the dose distribution along Y axis (in the plane perpendicular to the beam axis) in 10 cm depth.

![Figure 4. Comparison of 10 MV beam profile dose curve along the Y axis (crossline) between Geant4 and EGSnrc for a 4×4 cm$^2$ field in the homogeneous (water) phantom. The black line represents the dose distribution data obtained from EGSnrc, red line represents the data obtained from Geant4 and blue line represents the data obtained from measurement data.](image)

From figure 4, there is a great deviation between Geant4 and EGSnrc dose distribution in the high dose gradient area. The full width at half maximum (FWHM) of each graph are 3.95, 4 and 4.3 cm for Geant4, EGSnrc and measurement data. The MC EGSnrc and Geant4 calculated dose functions show very good agreement for distances up to 5 cm with literature data. For distances greater than 5 cm, the relative difference between both calculated data and literature data. MC study of dosimetric parameters and dose distribution are slightly larger. A larger difference of dose distribution between measurement and MC calculation was in the penumbra region because of the changes in voxel sizes and source geometry.
The dose along the central axis calculated with EGSnrc and Geant4 and measurement data for water phantom with field size 4×4 cm² is plotted in figure 5. This data produce the depth dose profiles with more than 7% dose discrepancy for this inhomogenous water phantom. The depth maximum of PDD is shifted to the big depth around 0.1 and 0.2 cm for EGSnrc and Geant4, respectively.

Figure 5. Comparison of 10 MV beam profile dose curve along the Y axis (crossline) between Geant4 and EGSnrc for a 4×4 cm² field in the homogeneous (water) phantom. The black line represents the dose distribution data obtained from EGSnrc, red line represents the data obtained from Geant4 and blue line represents the data obtained from measurement data.

3.2. Inhomogeneous phantom
An inhomogeneous phantom (water-aluminum-lung-water) with dimension of 39.5×30.5×30 cm³ was employed. Percent depth dose (PDD) and dose profile were also investigated by Geant4 and EGSnrc code system. PDD and profile dose scan along Z axis (depth) and Y axis (depth 10 cm), respectively. Figure 6 shows comparisons of PDD in inhomogeneous phantom at depth 10 cm for the 10 MV photon beam with calculation using Geant4 and EGSnrc with field size 4×4 cm² and SSD 120 cm. The density of water, aluminum, and lung are about 1.0, 2.7, and 0.26 g/cm³, respectively. For the inhomogeneous phantom, there is a great deviation in PDD and lateral profile between Geant4 and EGSnrc dose calculation.

Figure 6. Comparison of 10 MV beam PDD curve along the central axis between Geant4 and EGSnrc for a 4×4 cm² field in the inhomogeneous (water-aluminum-lung-water) phantom. The beam is incident on the top of phantom with its central axis on the center of the top water slab.

Figure 6 shows that there is difference between dose of presence of aluminium and lung as inhomogeneous by EGSnrc and Geant4. Form the figure, it is easy to see by looking at the plotted that there is a big deviation between dose distribution produced by EGSnrc and Geant4 in the lung region. The EGSnrc result shows that behind aluminium material, the dose was found to be increased by
6.41%, and behind lung material, the dose was found decreased by 2.93%. Behind aluminium material, the dose was found to be increased by 4.73%, and behind lung material, the dose was found decreased by 1.54% in the Geant4 result. In the lung inhomogeneity, the dose was decreased, which may be due to increased attenuation of radiation, and its high density. Behind aluminium inhomogeneity (among water and aluminium slice), the dose was increased, which may be due to decreased attenuation of radiation, and its less density. There was dose increasing in the border area between lung and water (10-15 cm). The attenuation coefficient of water is bigger than lung material. Some photons passed by lung was forwarded to water. Most photons with various energy would accumulated in the boundary and caused the rose of dose in this area.

PDD curve shows that there is dose reduced across the low density media both of EGSnrc and Geant4. Photon fields exposing low density material will undergo rose range of scattered electrons and decreased photon attenuation. Increased of electron range further restricts the scattering angle needed to keep the electrons within the field. The result of decreasing material density is small number of photons interacting and secondary electron depositing their energy further downstream if they deposit their energy in the field at all. A small field size (4×4 cm$^2$) used in this simulation results in more electrons leaving the volume of interest then entering it. This effect known as lateral electronic disequilibrium (LED) and produce a dose deficit in a low density region. In fact, photon and electron scatter change in the vicinity of the interface either reduced upon passing from high to low densities or rose when passing from low to high densities.

![Figure 7. Comparison of 10 MV beam lateral dose profile along the central axis between Geant4 and EGSnrc for a 4×4 cm$^2$ field in the inhomogeneous (water-aluminum-lung-water) phantom. The beam is incident on the top of phantom with its central axis on the center of the top water slab.](image)

Figure 7 shows the lateral dose profile a long Y axis (perpendicular with beam axis) in the inhomogeneous phantom by EGSnrc and Geant4 simulation. The big deviation founded on the penumbra region in the right side. The FWHM of EGSnrc and Geant4 curve are 4.4 and 4.05 cm, respectively. The effects of inhomogeneities on radiation dose distributions depend on the amount, density and atomic number of the inhomogeneity, as well as on the quality of the photon beam.

4. Conclusion
Monte Carlo simulations were performed using Geant4 [8] and DOSXYZnrc the user code of EGSnrc [9]. These codes use three-dimensional heterogeneous geometry and transports photons and electrons in the energy range from 1 KeV to some GeV. But, one of the limitation of EGSnrc is in order to calculate the neutron.
Acknowledgements
We are grateful to Tan Tock Seng Hospital, Singapore for the spectrum data for the Varian Clinac iX 10 MV photon beam beam. This study was partially supported by Penelitian Kerjasama Luar Negeri dan Publikasi Internasional Dikti, Ministry of Education Indonesia 2015 (312a/I1.C01/PL/2015).

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