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Original research article

EGSnrc application for IMRT planning☆

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ABSTRACT

The aim of this study was to describe a detailed instruction of intensity modulated radiotherapy (IMRT) planning simulation using BEAMnrc-DOSXYZnrc code system (EGSnrc package) and present a new graphical user interface based on MATLAB code (The MathWorks) to combine more than one. 3ddose file which were obtained from the IMRT plan.

This study was performed in four phases: the commissioning of Varian Clinac iX6 MV, the simulation of IMRT planning in EGSnrc, the creation of in-house VDOSE GUI, and the analysis of the isodose contour and dose volume histogram (DVH) curve from several beam angles. The plan paramaters in sequence and control point files were extracted from the planning data in Tan Tock Seng Hospital Singapore (multileaf collimator (MLC) leaf positions – bank A and bank B, gantry angles, coordinate of isocenters, and MU indexes).

VDOSE GUI which was created in this study can display the distribution dose curve in each slice and beam angle. Dose distributions from various MLC settings and beam angles yield different dose distributions even though they used the same number of simulated particles. This was due to the differences in the MLC leaf openings in every field. The value of the relative dose error between the two dose ditributions for "body" was 51.23 %. The Monte Carlo (MC) data was normalized with the maximum dose but the analytical anisotropic algorithm (AAA) data was normalized by the dose in the isocenter.

In this study, we have presented a Monte Carlo simulation framework for IMRT dose calculation using DOSXYZnrc source 21. Further studies are needed in conducting IMRT simulations using EGSnrc to minimize the different dose error and dose volume histogram deviation.

1. Introduction

The development of an advanced treatment technique in radiation therapy, such as intensity modulation or volumetric modulation arc therapy, requires an advanced quality assurance techniques to achieve high dose conformity to the tumor while minimizing damage to the organs at risk. The dynamic intensity modulated radiation therapy (IMRT) involves a series of small fields resulting in a complex intensity distributions, which was not present in the conventional radiation therapy using a static shaped beam. For accurate dose calculations, IMRT requires a model that is able to simulate complex and arbitrary fluence maps and accounts for electronic disequilibrium due to the highly heterogeneous and irregularly shaped medium. Different types of algorithms were used in IMRT dose calculation, such as the finite-size pencil beam algorithm (FSPB),[1–3] the convolution/superposition algorithm,[4–7] and Monte Carlo simulation.[8–16]

For IMRT, the optimal treatment plan requires a good agreement between planned and delivered dose distributions. Monte Carlo (MC) dose calculation algorithm is being recognized as the most accurate way of predicting patient dose.[9,11–13,16–20] The MC dose calculation can potentially offer some advantages over the conventional dose computation in complex geometries both in Linac

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MLC component and in the patient which are often found in IMRT cases. Fleckenstein et al.[11] validated the dosimetric accuracy for complex treatment deliveries using the volumetric modulated arc therapy (VMAT) technique obtained from Monte Carlo Geant4 and the dose distribution obtanined was compared to dose distributions planned. The dose distribution results showed mean deviations of less than 2.0 %. Geant4 application for the emission tomography (GATE) Monte Carlo simulation platform for clinical IMRT dosimetry was evaluated by Benhalouche et al.[21] The output factors showed a good agreement between MC simulation and the measurements results with a maximum error of 1.22 %. A fast MC program was used to verify 25 head-and-neck IMRT plans measured by film and diode dosimetry. Goetzfried et al. showed that an independent dose calculation verification of IMRT plans with a fast MC program has the potential to eclipse film dosimetry.[22]

During IMRT delivery, factors such as the radiation beam intensity, the monitor unit (MU) index, and the gantry movement can vary during treatment. IMRT beams consisted of a large number of segments (also known as control points) which depended on MLC opening, beam angles, and MU indexes. A new component module for the BEAM code[23] has been developed to facilitate the IMRT or VMAT simulation in EGSnrc Monte Carlo code package. Lobo and Popescu[24] present two new Monte Carlo sources for the DOSXYZnrc code (source 20 and 21), which can be used to compute the dose distributions with a large number of segments and different beam configurations. This code has been used by many researchers to simulate VMAT planning.[24–26] Zhan et al.[27] introduced a new transformation equation that can synchronize the coordinate of CT images and DOSXYZnrc that facilitate simulation by using CT data.

In this study, DOSZYZnrc Monte Carlo code was used to simulate IMRT planning with seven different beam angles. Previous studies were conducted by Diragyussa et al. using the same EGSnrc code for VMAT simulation with a very large number of beam angles and only one dose distribution is obtained at the end of simulation.[28]

The IMRT simulation in this study consisted of 7 beam angles so that at the end of this simulation there were 7 different dose distributions due to these different MLC openings and beam angles. Therefore, a special code is needed to combine these dose distributions. The aim of this study was to describe a detailed instruction of IMRT planning simulation using EGSnrc/BEAMnrc-DOSXYZnrc code system and present a new graphical user interface based on MATLAB code to combine more than one. 3ddose file obtained from the IMRT plan.

2. Methods

This study was performed in four phases: the commissioning of Varian Clinac iX6 MV, the simulation of IMRT planning in EGSnrc, the creation of in-house VDOSE GUI, and analysis of the isodose contour and dose volume histogram (DVH) curve from several beam angles. The computation in this work utilized a personal computer with four AMD Opteron 2.1 GHz 16-core processors, and 192 GB DDR3 RAM.

2.1. Commissioning of varian clinac iX6 MV photon beam

A Varian Clinac iX linear accelerator (Linac) of 6 MV photon beam was modeled using the EGSnrc-based BEAMnrc Monte Carlo code. The linear accelerator head geometry and the measurement data have been provided by the manufacturer (Varian Medical Systems, Palo Alto, California, USA) and Tan Tock Seng Hospital (TTSH) Singapore, respectively. The measured data for the commissioning process were acquired in a homogeneous water phantom with a

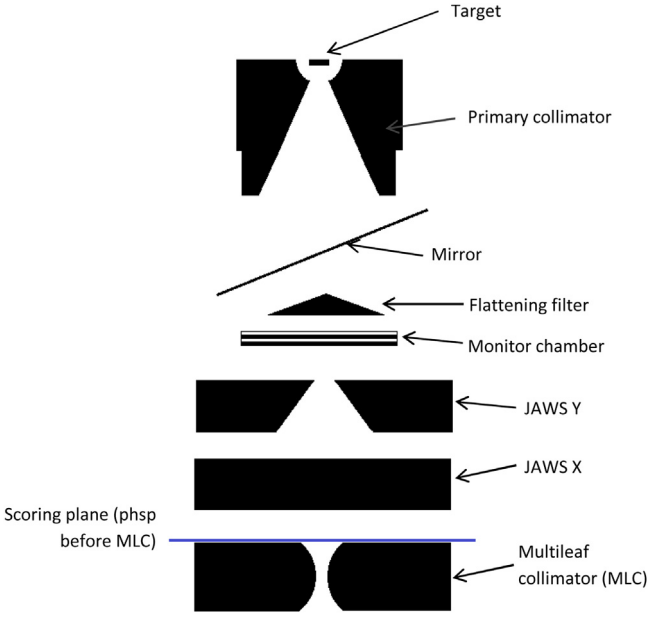

Fig. 1. A schematic diagram of Varian Clinac iX6 MV photon beam.

dimension of $40 \times 40 \times 40$ cm^3, which was placed at a source-to-surface distance (SSD) of 100 cm and a field size of 10×10 cm^2.

The Linac was structured in the following order: a target slab made of Tungsten and Copper, a primary collimator made of Tungsten, a flattening filter made of Copper, an ion chamber, JAWS (Tungsten) and multileaf collimator (Tungsten), as provided by the manufacturer including its density and chemical structure (Fig. 1). All materials used in the MC simulation were extracted from the 700ICRU PEGS4 (pre-processor for Electron Gamma Shower) cross section data which were available in EGSnrc. To achieve an excellent statistical uncertainty, a large number of histories were simulated (for example, at least 300 million particles are needed to obtain good statistical uncertainty (less than 1 %) in a simple water phantom with dimension of $40 \times 40 \times 40$ cm^2). The modeling of Linac geometry is modulated to reach a good match between the calculated and measured dose distributions (deviation of not more than 5 %). The distribution of charge, energy, position and direction of particles at a certain scoring plane was stored in the phase space (phsp) file. This file can be used as a source in the subsequent simulation. The field size setting was performed by adjusting the MLC opening.

For the commissioning process, the Monte Carlo simulated percentage depth dose and dose profile curves for the Varian Clinac iX6 MV photon beam were compared with the measured one for a field size of 10×10 cm^2. The doses were normalized relative to the d_{max} dose. The statistical error in the MC simulation is < 4.67 % on average. The maximum percentage dose difference between the measured and Monte Carlo curves beyond the build-up region is < 2 %. From these results, the optimal incident electron beam parameters for this 6 MV photon beam were: energy = 6.4 MeV; full width at half maximum (FWHM) = 0.15 cm.[29] Therefore, MC algorithm used in this study had been commissioned to match the measurement results and had been thoroughly tested and benchmarked against the measurement results for the 6 MV photon beam.

2.2. Monte Carlo simulation for IMRT plan

IMRT treatment was achieved by using the dynamic MLC sliding window technique. There are many possible ways to model Varian or Elekta's MLC using EGSnrc Monte Carlo techniques. The complex geometry of the MLC (i.e. tongue and groove, leaf width, leaf tip

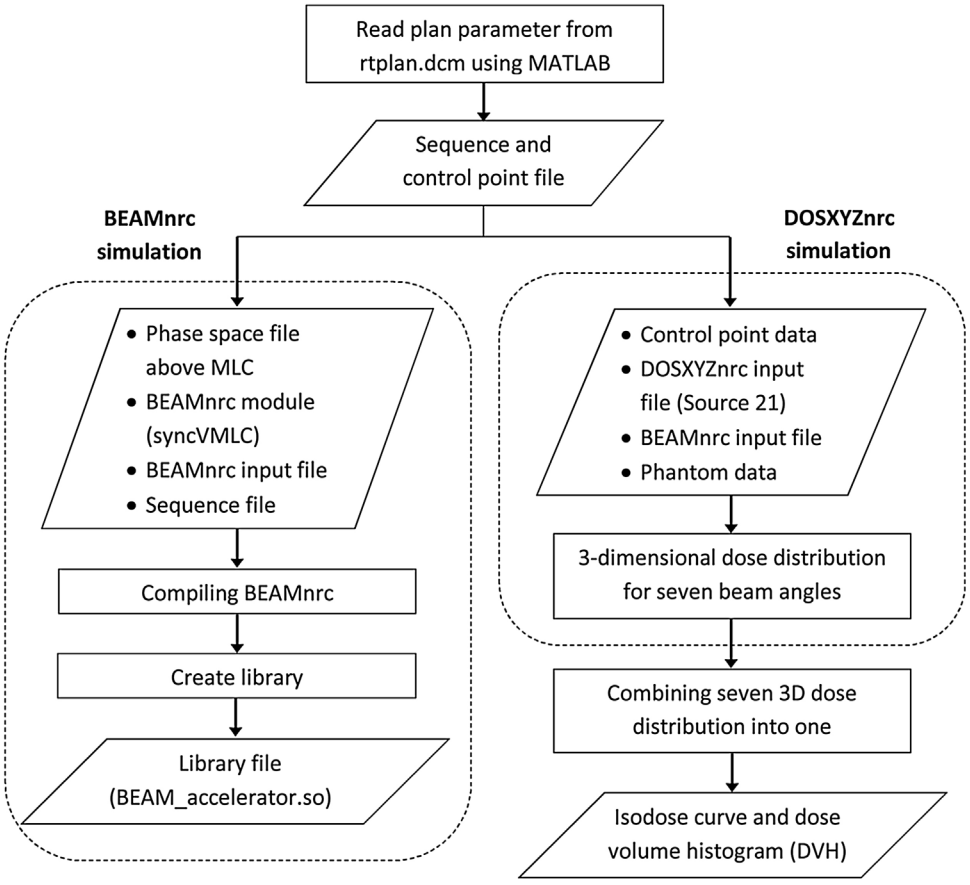

Fig. 2. A research flowchart of EGSnrc IMRT simulation.

width, leaf gap, drive screw hole, etc.) provided by the manufacturer performs accurate simulation computationally; however, it took a lot of time. Varian has three types of MLC, i.e., MLC Millenium 80 and 120 leafs and HDMLC 120 leafs. In this Linac simulation, the MLC Millenium 120 leafs was used to define the field sizes.

According to Asuni et al.,[25] there are three main steps, i.e., pre-simulation, simulation, and post-simulation. In the pre-simulation step, the verification of the plans and the input files for the simulation of the individual personal computer were created and organized. The pre-simulation step managed the simulations of the created input files composed of sequence and control point files. Simulations with DOSXYZnrc source 21 are carried out at the simulation stage which results in several dose distributions with different beam angles. In the post simulation step, the 3D dose distribution from seven datasets was combined into the MC accumulated dose.

Fig. 2 shows the research flowchart of EGSnrc IMRT simulation in this study. BEAMnrc and DOSXYZnrc.[23],[30] Monte Carlo codes were used for all of the Linac components including the MLC part and the dose calculation in the phantom, respectively. The simulation parameters were provided in the planning using analytical anisotropic algorithm (AAA) at the TTSH hospital. The dose distributions of AAA and DOSXYZnrc simulations were analyzed using dose volume histogram and 2D isodose curve.

a) Read plan parameter

The parameter plan used in this study was extracted from of DICOM data (rtplan.dcm) for prostate cancer obtained from TTHS, Singapore. The plan data contained the geometry data and the beam information including beam angles, collimator openings, isocenter coordinates, radiation beam positions and size designs, and doses on planning tumor volume (PTV) and organ at risk (OAR). These data were used as the input for the subsequent simulation stage.

The plan data was read by using the MATLAB code to get the position data for each MLC leafs, bank A and bank B. The data was stored in the sequence file containing the MU index and followed by the MLC opening for each beam angle. The MLC opening in the file was compiled into a BEAM shared library and used as one input in DOSXYZnrc source 21.

The rtplan.dcm also contained some information regarding the isocenter coordinates, gantry angles, collimator angles, and MU index which acted as DOSXYZnrc control points. Control point settings in DOSXYZnrc source 21 were performed on several parameters, including xiso (cm), yiso (cm) and ziso (cm) which are the x, y, z coordinates in the isocenter, theta angle (degree), phi angle (degree), phicol angle, and source-to-axis-distance (SAD). Theta expressed angles between the + z direction and a line joining the center of the beam with the isocentre, whereas the phi angles expressed the angle between the + x direction and the projection on the xy plane of the line joining the center of the beam on the phantom surface to the isocenter on the xy plane, respectively. Phicol angle is the angle formed by a source plane perpendicular to the beam direction (Walters, et al. 2018). To convert the angles in this simulation, the equation introduced by Zhan et al.[27] was used (equation number (7), (8), and (10)). If the couch angle = 0°, collimator angle = 0° and a certain gantry angle in plan parameter, tetha = 90°, phi = gantry angle – 90°, and collimator angle = 270°.

a) BEAMnrc simulation

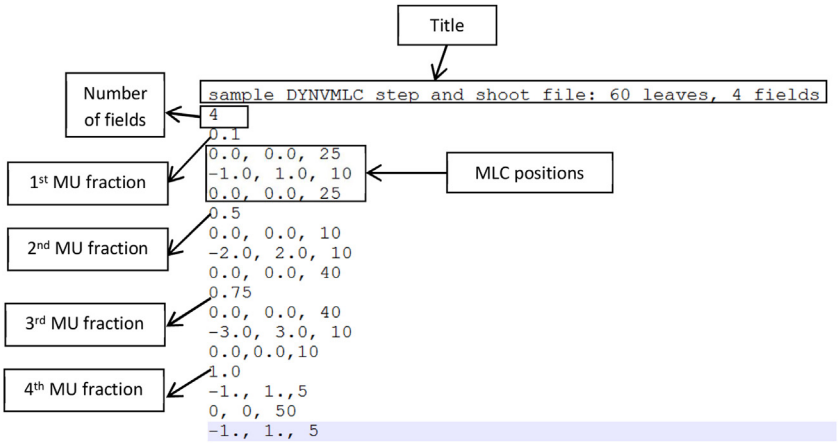

Fig. 3. An example of the sequence file structure.

Table 1
The BEAMnrc transport parameters.

BEAMnrc parameters	Value
Global ECUT	0.7
Global PCUT	0.01
Global SMAX	5
ESTEPE	0.25
XIMAX	0.5
Boundary crossing algorithm	PRESTA-I
Skin depth for BCA	0
Electron-step algorithm	PRESTA-II
Spin effects	On
Brems angular sampling	Simple
Brems cross-sections	BH
Bound Compton scattering	Off
Pair angular sampling	Simple
Photoelectron angular sampling	Off
Rayleigh scattering	Off
Atomic relaxations	Off
Electron impact ionization	Off

There were six files prepared for the IMRT simulation on EGSnrc: BEAMnrc (synchronized module, phsp file before MLC, BEAMnrc input file, and sequence file) and DOSXYZnrc (beam shared library and DOSXYZnrc input file). All BEAMnrc transport parameters are shown in Table 1. Any parameters not shown were set to default parameters in DOSXYZnrc.

- *Phase space (phsp) file before MLC*

Phsp files for the Varian Clinac iX6 MV photon beam were created by using the EGSnrc\ BEAMnrc system. As in the commissioning process, the cut-off energies used in the simulations were ECUT =0.7 MeV and PCUT =0.01 MeV for electrons and photons, respectively. The phsp file was scored above MLC and used as input in the IMRT simulation using DOSXYZnrc.

- *BEAMnrc module, input file, and sequence file*

SYNCVMLC is a component module (CM) similar to DYNVMLC which allows the synchronization between the motion of the MLC and other dynamic components of the model. The CM is a contribution from Lobo and Pospecu (2011). In particular, this CM allows the modeling of different beam configurations by synchronizing the source (phsp file) with the phantom movement using source 21 in DOSXYZnrc. There were other types of modules such as SYNCJAWS and SYNCMLCE which were used to synchronize JAWS and MLC Elekta, respectively.

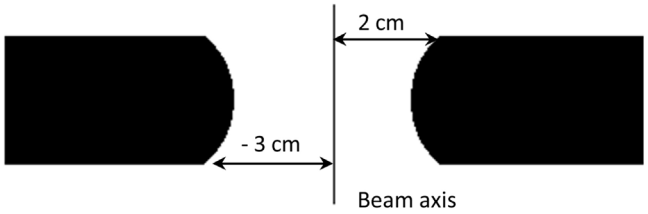

Fig. 4. MLC position in BEAMnrc simulation.

The input file for BEAMnrc was similar to the input for VARMLC for Varian Linac. The sequence file was input in the file which contains the leaf opening data. The sequence file consists of a title, number of fields, MU fractions, and a block of 60 leaf pairs MLC positions (Fig. 3). Using this file, it was possible to model the MLC movement. In the sequence file example, there were 4 dynamic fields. The MU index was 0.1, 0.5, 0.75, and 1.0. From MU index 0.0 to 0.1 (10 % of the simulation), the bank A and bank B of the MLC from leaf 26–35 were separated by 2 cm (1 cm from the beam axis) and the others (1–25 and 36–60) are closed (Fig. 3).

- *Beam shared library*

DOSXYZnrc and other EGSnrc user code allow the user to use a full BEAM simulation as a particle source (instead of a stored phsp file). In order to use this source, the BEAM accelerator code must first be compiled as a shared library. Once an accelerator has been built, it can be compiled as a shared library by going into $EGS HOME/BEAM_accelerator and typing: make library. The BEAM_accelerator was created as a library file and used in DOSXYZnrc as an input file (Fig. 4).

a) DOSXYZnrc simulation
b) *DOSXYZnrc input file (Source 21)*

DOSXYZnrc has eleven types of sources. Source 20 and source 21 allow to simulate continuous motion of the phsp source relative to the DOSXYZnrc phantom over specified ranges of incident directions, SSD's and isocentre coordinates developed by Lobo and Popescu (2011). A simple example of an input segment for nset = 3 is shown in Fig. 5. 0, 0, and 10 are the x, y and z isocentre coordinates in this dataset with a source to axis distance (SAD) = 55.68 cm.

- *Phantom from CT data*

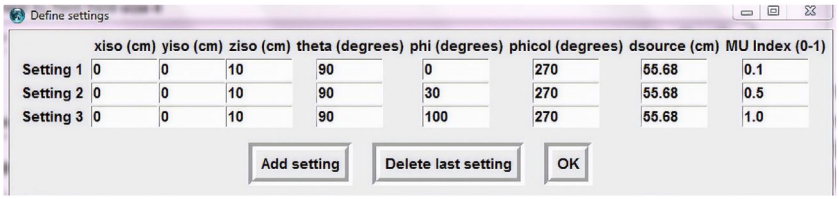

Fig. 5. The source 21 setting to locate the phase space source.

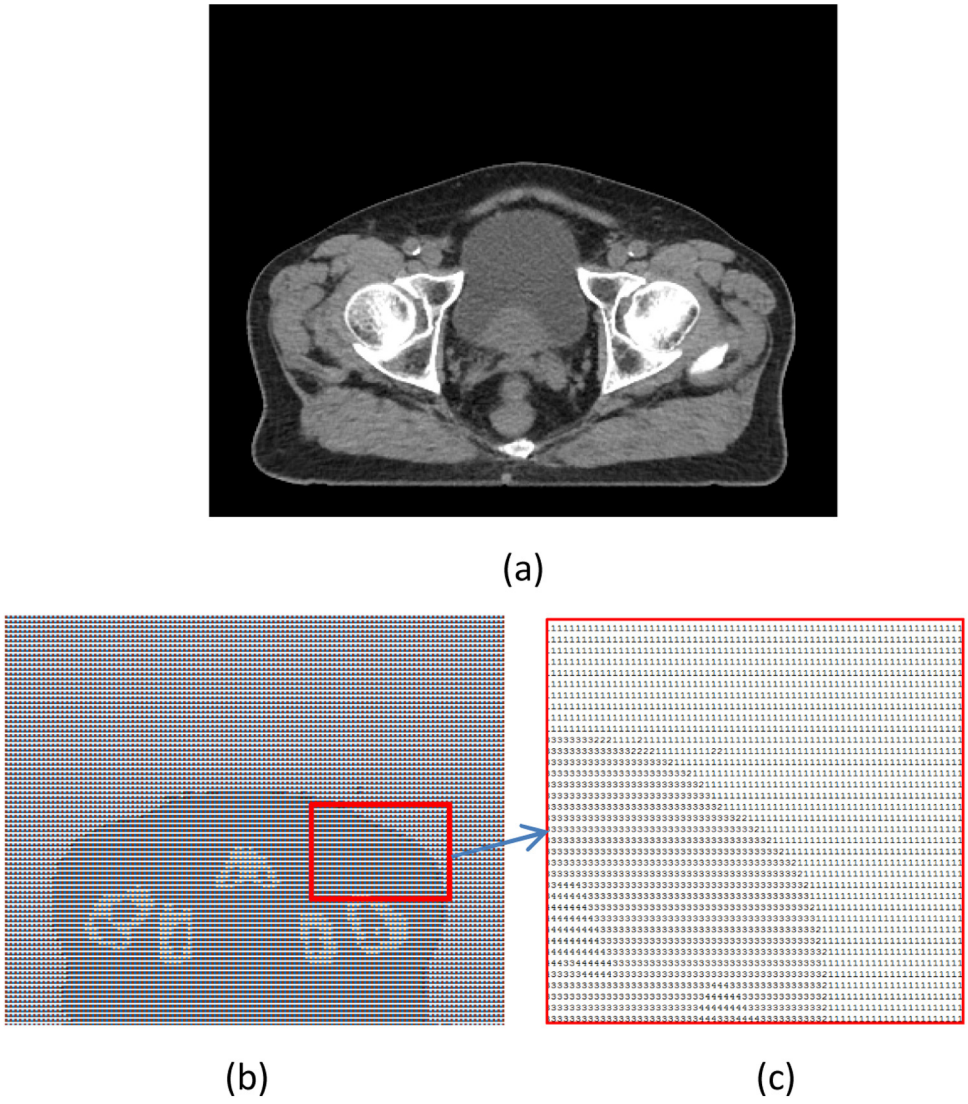

Fig. 6. The DICOM image of a prostate phantom as shown by dicompyler and a DICOM slice after converting to a numerical value using ctcreate (a) CT image, (b) CT image has been converted to egsphant using ctcreate (the CT images convert to numbers depend on the voxel density), and (c) the zoom image of red square box.

The phantom used was converted from the DICOM image obtained at the Tan Tock Seng Hospital, Singapore. The data must be converted to DICOM CT scan images using the ctcreate program (Fig. 6). This program can convert CT data into virtual phantoms in a numerical form and can be used as an input in DOSXYZnrc with. egsphant extension. In this process, it was necessary to adjust the size of the voxel in the phantom as desired as well as the amount of material and type of phantom material. The data obtained from the hospital were CT data with a grayscale image formed during scanning. With ctcreate, the converted CT data will be a set of numbers which depend on the constituent material (Fig. 6). The results of the ctcreate conversion were obtained in a. egsphant file consisting of numbers 1, 2, 3, and 4. The numbers in the. egsphant file indicate the type of the material and the density of each phantom compiler. Numbers 1, 2, 3 and 4 represent water, lung, tissue, and bone material, respectively. The volume surrounding the water phantom was set to air and set to 0 with the dose converted to zero. The ctcreate settings were created using the EGSnrc default settings so the material displayed was based on the grayscale shown by ctcreate.

The initial CT data has a dimension of 512×512 pixels with 149 slices. After being converted using ctcreate, the phantom was changed to a small size volume element (voxel), e.g., $127 \times 87 \times 104$ in the x, y, and z direction with widths of 0.37 cm, 0.37 cm, and 0.4 cm, respectively. The particle history number used was 10^9

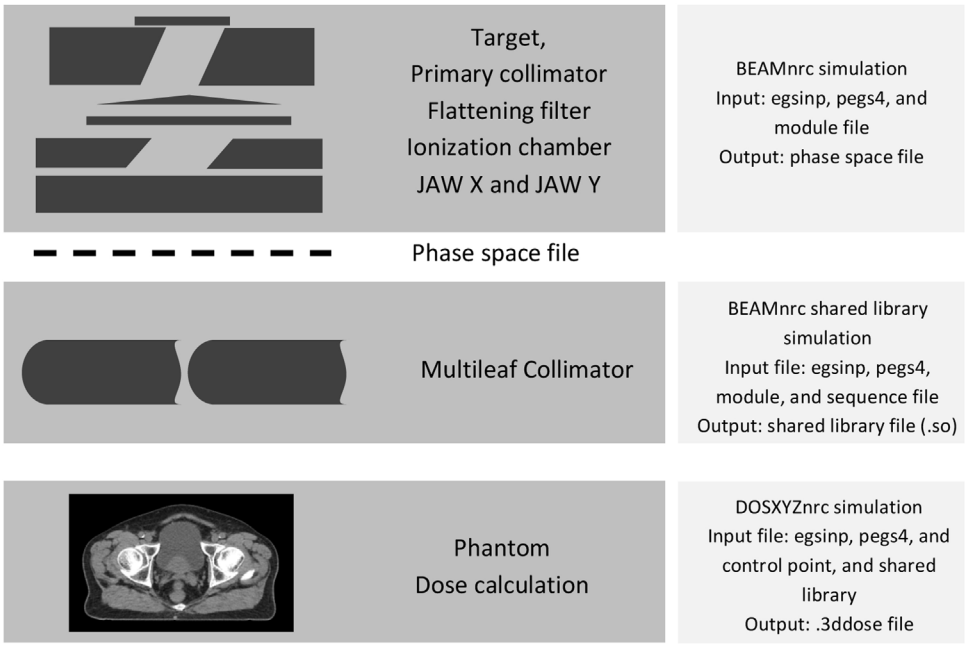

Fig. 7. An illustration of Monte Carlo simulation performed in this study.

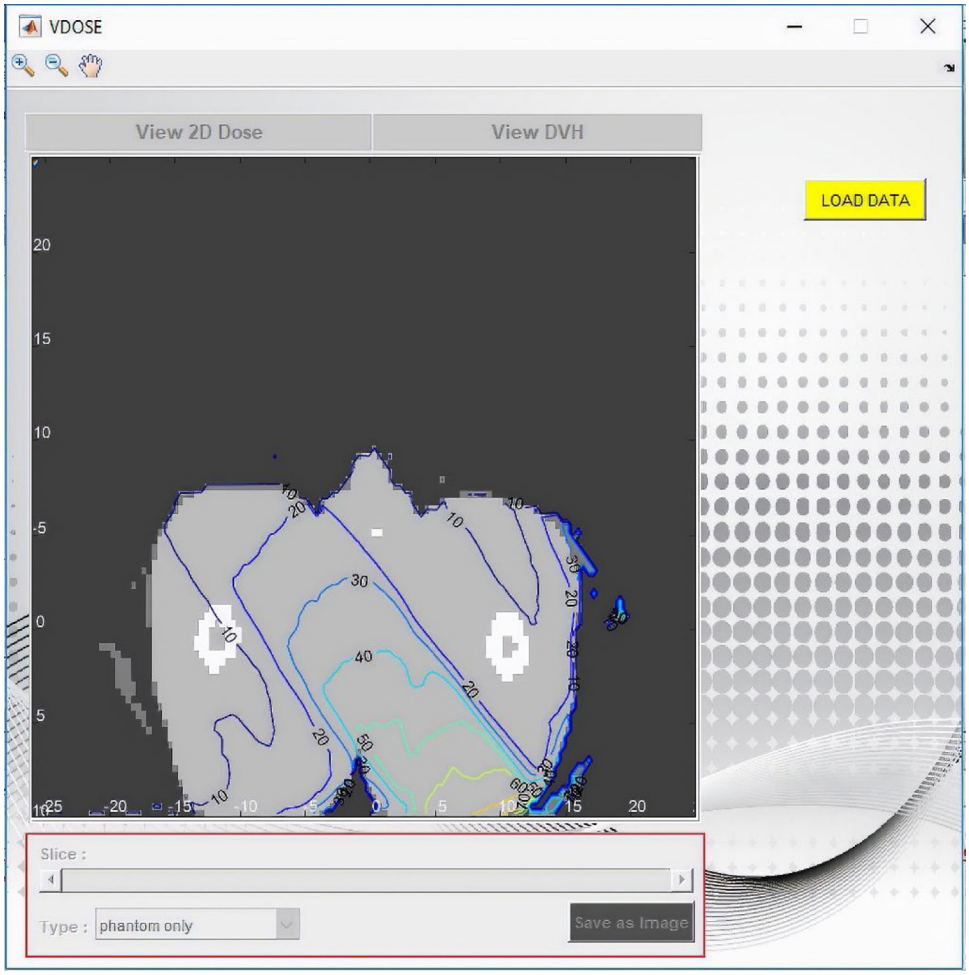

Fig. 8. VDOSE graphical user interface.

Table 2
List of beam angles and number of MLC openings simulation.

No	Gantry angles (°)	Tetha angles (°)	Phi angles (°)	Collimator angles (°)	Number of MLC openings
1	223	90	133	270	274
2	275	90	185	270	160
3	335	90	245	270	289
4	25	90	295	270	254
5	85	90	355	270	165
6	129	90	39	270	163
7	180	90	90	270	252

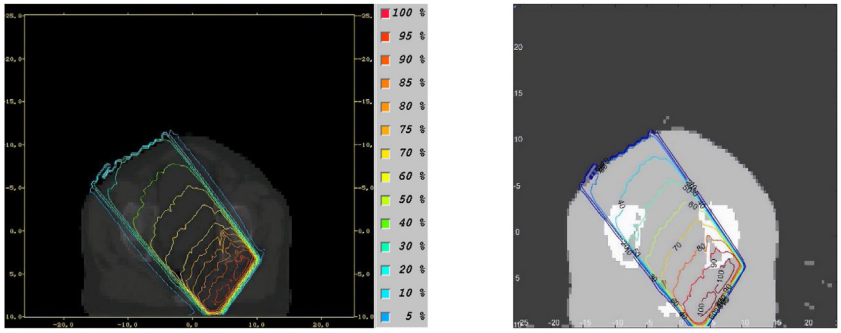

Fig. 9. The comparison of dose distribution from (a) DOSXYZ_SHOW and (b) VDOSE GUI.

particles for each irradiation, accumulating to the total history of 3×10^9 particles. The time required to do each irradiation is 24 h which accumulates to 7 days for the whole processs. The number of histories required in each run to get a desired statistical uncertainty was dependent on the field size, voxel size and the photon beam energy.

Generally, the overall scheme of the Monte Carlo simulation of this study is explained in Fig. 7. Three steps of simulation were conducted. The phsp file was only scored below JAW X or above MLC components and used for all simulation in BEAMnrc shared library and DOSXYZnrc simulation.

2.3. In-house VDOSE GUI

The GUI required only the. 3ddose and. egsphant files. The. 3ddose file obtained from each simulation with different beam angle can be read by dosxyz_show; however, the dosxyz_show program still has some drawbacks in displaying some. 3ddose data at the same time, especially for IMRT. In IMRT simulation, each beam angle produces a different. 3ddose file which accumulated to seven. 3ddose files in the final simulation result. Therefore, a new in-house program is needed in order to combine the. 3ddose file and immediately display the results of the irradiation simulation on. egsphant. The program can display the isodose curve and DVH for one or many. 3ddose files. Fig. 8 shows the appearance of the VDOSE GUI based on MATLAB.

2.4. Isodose curve and DVH analysis

DOSXYZnrc outputs are. egslst,. 3ddose, and. egslog files. The egslst contains the total CPU time during the simulation. Meanwhile, the. 3ddose file contains the information of the number of voxels, voxel boundaries, dose value, and dose error. This file consists of 6 blocks. The first block showed the number of voxels in the x, y, z directions, while the second, third, and fourth blocks represented the voxel boundaries (cm) in the x, y, z directions, respectively. The fifth block displayed dose values array by (nx × ny × nz) values. This dose block had a different structure depending on the operating system (Windows and LINUX) that was used. The sixth block consists of error values array (relative errors) by (nx × ny × nz) values.[30]

2D isodose curve is a dose distribution showing the dose distribution in a cross-sectional area with a certain depth in the patient and normalized with respect to the maximum dose. These curves represent a dose distribution in the target, OAR and normal tissue. DVH for tissue and another material in a phantom was analyzed. The dose distribution from. 3ddose file was extracted to obtain the percentage dose in the certain phantom material.

3. Results and discussion

3.1. Plan parameter extraction

All parameters obtained from the DICOM data (rtplan.dcm) were used as the input data for the BEAMnrc and DOSXYZnrc simulation. There were seven beam angles in this treatment; therefore, seven simulations were performed on each of the BEAMnrc and DOSXYZnrc simulations. BEAMnrc was used to design head linac and was commissioned with the measurement data including the size of the JAWS and MLC on the modeled Linac. In the rtplan file there were several data that will be converted into two files for the MLC sequence file and control points data used in the EGSnrc simulation. The information on fractionation (i.e. the number of MU per beam) was located under the DICOM field "FractionGroupSequence" under which each individual beam was listed as a subfield. In the planning data, the collimator angle was 0° and later converted to 270° based on the formula introduced by ref. [27] ($Collimator\ angle_{DOSXYZnrc} = -90 - Collimator\ angle_{Planning}$) (Table 2).

The MLC opening will change its shape according to the Varian Eclipse treatment planning system (TPS) settings. The change in the opening of MLC will also depend on the MU index given during irradiation. The MU index value given is distributed from 0 to 1. The isocenter coordinate in the x, y and z directions were −0.00025 cm, 0.00032 cm, and −0.1498 cm, respectively.

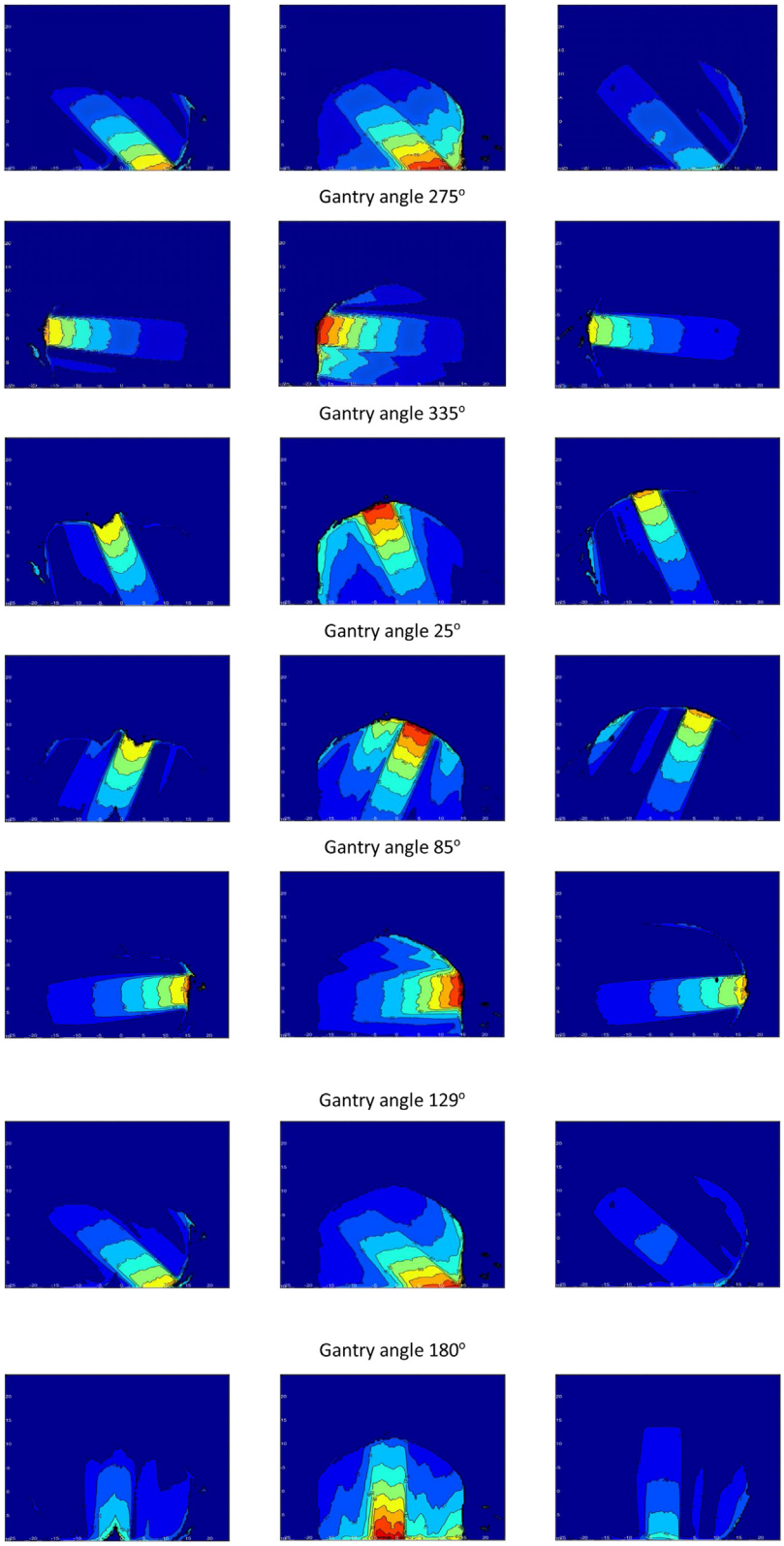

Fig. 10. The isodose distributions on an axial slice using VDOSE GUI for seven beam angles in slice (a) 26th, (b) 53rd and (c) 82nd.

The phicol angle was the result of the transformation of the gantry angle that was found in each irradiation angle which was typical for each irradiation. The results of dose calculation produce. egsphant and a. 3ddose file that was used to plot the isodose curve in DOSXYZ_SHOW and our in-house software. There was an example of the results of the. 3ddose file using DOSXYZ_SHOW (Fig. 9). The isodose curve shown had a similar shape to that of the isodose curve by dosxyz_show, i.e. the color difference showed the percentage of the doses contained in the area.

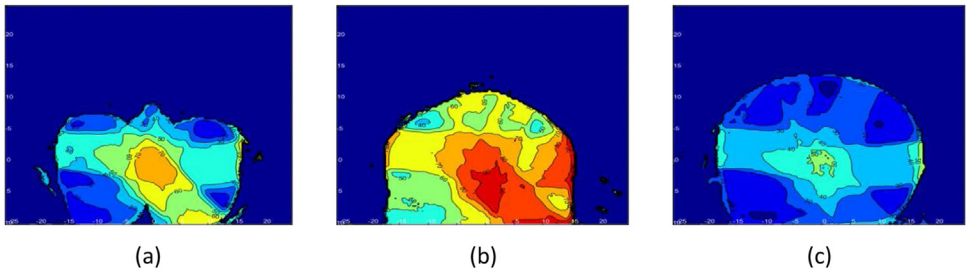

Fig. 11. The isodose distributions on an axial slice for the dose combination from seven beam angles in slice (a) 26th, (b) 53rd and (c) 82nd.

3.2. Validation VDOSE GUI

Both coplanar and non-coplanar plans were generated for each IMRT planning. The DOSE GUI can assist to combine more than one dose distribution in one. 3ddose file and calculate the DVH while representing the isodose contours in the axial direction. The isodose produced by the MATLAB code was validated with the DOSXYZ_SHOW. The DOSXYZ_SHOW can display contours and phantom together by providing input files in the form of dose data (.3ddose file) and phantom data (.egsphant file). In this section, we compared the dose contours obtained from DOSXYZ_SHOW and VDOSE GUI (Fig. 9). Similar contours were produced.

3.3. Dose distribution from seven beam angles

The resulting isodose distributions for each beam angle in slice 26th, 53rd and 82nd for beam angles 223°, 275°, 335°, 25°, 85°, 129°, and 180° were shown in the Fig. 10 below. The dose distribution from different MLC settings and beam angles, yield different dose distributions even though they used the same number of simulated particles. Different MLC opening caused different isodose contours for each beam angles. The dose was normalized to 100 % in the maximum dose for all slices. The phantom geometry was not shown in each beam and slice. The different color contours represent different dose values.

The simulation time was seven days (24 h for each beam angles in average) which was influenced by some simulation parameters, e.g., the number of the simulated particles, the cut-off energies (for photon and electron), variance reduction techniques, beam energy, the number of segments or control points), the dimensions and voxel sizes of the patient voxelized phantom, etc. A more detailed study of the effect of these factors on the total simulation time could be done in order to minimize times and costs. This work should be compared with another Monte Carlo code like MCNPX or Geant4 to get the fast computation and better results.

3.4. Combination of. 3ddose file

The GUI can show the isodose curve and dose volume histogram (DVH) from the simulation results that have been carried out. The. egsphant data was derived from the CT data which was converted using ctcreate. The isodose curve shown in the GUI was similar to that of the isodose curve from dosxyz_show, i.e. the color difference which showed the percentage of the doses in the area.

The dose distributions along the axial (XY) planes for the the prostate case was shown in Fig. 11 with 95 %, 80 %, 60 %, 40 %, and 20 % isodose distributions represented by the dark red, red, yellow, and dark yellow lines, respectively. The resulting contour is not smooth, which is probably caused by a small number of simulated particles (Fig. 12).

The results of the isodosis curve shown from the simulation result (MC simulation) show a different percentage comparison with the results of the AAA isodosis curve. The isodose contour and

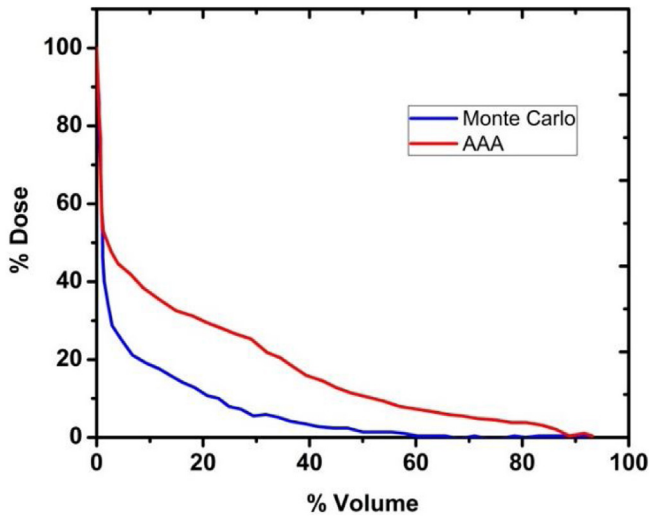

Fig. 12. Comparison of dose volume histogram for body obtained from EGSnrc Monte Carlo simulation and anisotropic analytical algorithm (AAA).

DVH curve formed from the IMRT simulation using EGSnrc have a pattern that is similar to the isodosis and DVH from AAA TPS. Although there are still differences in some slices. The smallest dose of the simulation results is 10 %; for the same position on the TPS curve, the dose is 30 %. The biggest dose from the simulation results shows a value of 80 % while the largest TPS curve results is 106 %. This is possible because of differences in dose normalization. The MC data was normalized with the maximum dose but the AAA data was normalized by the dose in the isocenter.

The figure above shows the comparison of dose volume histograms for body obtained from simulation and AAA. The value of the relative dose error in the two dose ditributions is 51.23 %. In the DVH, for MC simulaition shows that 20 % of the body volume gets about 30 % of the prescribed dose. This value is considerably different from the dose calculated with AAA. Doses of 50–100% do not affect the body volume. Further studies are needed in conducting IMRT simulations using EGSnrc to minimize the different dose error.

4. Conclusions

In this study, we have presented a Monte Carlo simulation framework for IMRT dose calculation using DOSXYZnrc source 21. The isodose contour and DVH curve formed from the IMRT simulation using EGSnrc have a pattern that is similar to the isodosis and DVH from AAA TPS. Although there are still differences in some slices. Further studies are needed in conducting IMRT simulations using EGSnrc to minimize the different dose error. Furthermore, the use of MC for dose simulation must continue to obtain better results and shorter simulation times using other codes, such as MCNP and Geant4.

Author agreement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Financial disclosure

I certify that I have affiliations with or financial involvement (eg., employment, consultancies, honoraria, stock ownership or options, expert testimony, grants and patents received or pending, royalties) with an organization or entity with a financial interest in, or financial conflict with, the subject matter or materials discussed in the manuscript and all such affiliations and involvements are disclosed on the title page of the manuscript.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.rpor.2020.01.004.

References

1. Jelen U, Sohn M, Alber M. A finite size pencil beam for IMRT dose optimization. *Phys Med Biol*. 2005;50:1747–1766.
2. Jelen U, Alber M. A finite size pencil beam algorithm for IMRT dose optimization: Density corrections. *Phys Med Biol*. 2007;52:617–633.
3. Sikora M, Muzik J, Söhn M, Weinmann M, Alber M. Monte Carlo vs. Pencil beam based optimization of stereotactic lung IMRT. *Radiat Oncol*. 2009;4:64.
4. Ahnesjö A. Collapsed cone convolution of radiant energy for photon dose calculation in heterogeneous media. *Med Phys*. 1989;16:577–592.
5. Naqvi SA, Earl MA, Shepard DM. Convolution/superposition using the Monte Carlo method. *Phys Med Biol*. 2003;48(14):2101–2121.
6. Vanderstraeten B, Reynaert N, Paelinck L, et al. Accuracy of patient dose calculation for lung IMRT: A comparison of Monte Carlo, convolution/superposition, and pencil beam computations. *Med Phys*. 2006;33(9):3149–3158.
7. Muralidhar KR, Murthy NP, Raju AK, Sresty N. Comparative study of convolution, superposition, and fast superposition algorithms in conventional radiotherapy, three-dimensional conformal radiotherapy, and intensity modulated radiotherapy techniques for various sites, done on CMS XIO planning system. *J Med Phys*. 2009;34(1):12–22.
8. Ma C-M, Pawlicki T, Jiang SB, et al. Monte Carlo verification of IMRT dose distributions from a commercial treatment planning optimization system. *Phys Med Biol*. 2000;45:2483–2495.
9. Laub W, Alber M, Birkner M, Nusslin F. Monte Carlo dose computation for IMRT optimization. *Phys Med Biol*. 2000;45:1741–1754.
10. Wang L, Yorke E, Chui C-S. Monte Carlo evaluation of 6 MV intensity modulated radiotherapy plans for head and neck and lung treatments. *Med Phys*. 2002;29:2705.
11. Fleckenstein J, Jahnke L, Lohr F, Wenz F, Hesser J. Development of a Geant4 based Monte Carlo Algorithm to evaluate the MONACO VMAT treatment accuracy. *Z Med Phys*. 2013;23(1):33–45.
12. Yang J, Li J, Chen L, et al. Dosimetric verification of IMRT treatment planning using Monte Carlo simulations for prostate cancer. *Phys Med Biol*. 2005;50:869–878.
13. Dogan N, Siebers JV, Keall PJ, et al. Improving IMRT dose accuracy via deliverable Monte Carlo optimization for the treatment of head and neck cancer patients. *Med Phys*. 2006;33:4033.
14. Bol GH, Hissoiny S, Lagendijk JJW, Raaymakers BW. Fast online Monte Carlo-based IMRT planning for the MRI linear accelerator. *Phys Med Biol*. 2012;57:1375–1385.
15. Conneely E, Alexander A, Ruo R, Chung E, Seuntjens J, Foley MJ. Monte Carlo investigation of collapsed versus rotated IMRT plan verification. *J Appl Clin Med Phys*. 2014;15(3):4681.
16. Chandroth MM, Venning A, Chick B, Waller B. Effects of contrast materials in IMRT and VMAT of prostate using a commercial Monte Carlo algorithm. *Australas Phys Eng Sci Med*. 2016;39(2):547–556.
17. Lovelock DM, Chui CS, Mohan R. A Monte Carlo model of photon beams used in radiation therapy. *Med Phys*. 1995;22(9):1387–1394.
18. Jeraj R, Keall P. Monte Carlo-based inverse treatment planning. *Phys Med Biol*. 1999;44:1885–1896.
19. Yani S, Dirgayussa IGE, Rhani MF, Soh RCX, Haryanto F, Arif I. Monte Carlo study on electron contamination and output factors of small field dosimetry in 6 MV photon beam. *Smart Sci*. 2016;4(2):87–94.
20. Yani S, Rhani MF, Soh RCX, Haryanto F, Arif I. Monte Carlo simulation of Varian Clinac iX 10 MV photon beam for small field dosimetry. *International Journal of Radiation Research*. 2017;15(3):275–282.
21. Benhalouche S, Visvikis D, Maitre AL, Pradier O, Boussion N. Evaluation of clinical IMRT treatment planning using the GATE Monte Carlo simulation platform for absolute and relative dose calculations. *Med Phys*. 2013;40(2).
22. Goetzfried T, Rickhey M, Treutwein M, Koelbl O, Bogner L. Monte Carlo simulations to replace film dosimetry in IMRT verification. *Z Med Phys*. 2011;21(1):19–25.
23. Rogers DWO, Walters B, Kawrakow I. *BEAMnrc users manual*. Ottawa: National Research Council of Canada; 2018 (Chapter 15).
24. Lobo J, Popescu IA. Two new DOSXYZnrc sources for 4D Monte Carlo simulations of continuously variable beam configurations, with applications to RapidArc, VMAT, TomoTherapy and CyberKnife. *Phys Med Biol*. 2010;55(16):4431–4443.
25. Asuni G, van Beek TA, Venkataraman S, Popescu IA, McCurdy BMC. A Monte Carlo tool for evaluating VMAT and DIMRT treatment deliveries including planar detectors. *Phys Med Biol*. 2013;58:3535–3550.
26. Popescu IA, Atwal P, Lobo J, Lucido J, McCurdy BMC. Patient-specific QA using 4D Monte Carlo phase space predictions and EPID dosimetry. *J Phys Conf Ser*. 2015;573:012004.
27. Zhan L, Jiang R, Osei EK. Beam coordinate transformations from DICOM to DOSXYZnrc. *Phys Med Biol*. 2012;57(24):N513–N523.
28. Dirgayussa IGE, Yani S, Pratama D, Rhani MF, Soh RCX, Haryanto F. *The effect of inaccuracy of MLC leaf position against dose distribution on VMAT delivery technique using EGSnrc monte carlo simulation. Proceedings of 2018 2nd international conference on biomedical engineering: Smart technology for better society, IBIOMED 2018*; 2018.
29. Dirgayussa IGE, Yani S, Rhani MF, Haryanto F. Commissioning of a varian clinac iX 6 MV photon beam using Monte carlo simulation. In: *AIP conference proceedings.*; 2015, 1677, 040006.
30. Walters B, Kawrakow I, Rogers DWO. *DOSXYZnrc users manual*. Ottawa: National Research Council of Canada; 2018 (Chapter 4).