Modelling Radiation Dose Distribution within Thorax using Monte Carlo Package Codes

Sri Herwiningsih¹, Andrew Fielding²

¹Department of Physics, Faculty of Science, Universitas Brawijaya, Indonesia
²School of Chemistry, Physics and Mechanical Engineering, Faculty of Science and Technology, Queensland University of Technology, Australia

*Corresponding author : herwin@ub.ac.id

Abstract. In radiotherapy practice, it is difficult to measure radiation dose within patient anatomy. Although it is possible to do so, the technique would cause discomfort and pain to the patient due to the insertion of the radiation detector inside the patient’s body. Monte Carlo simulation offer a non-invasive technique to estimate radiation dose distribution within the patient’s body. This paper presents a work on modelling the radiation dose distribution within the thorax region in lung cancer treatment cases. EGSnrc/DOSXYZnrc Monte Carlo codes were employed in this study. Patient anatomy was modelled by converting the images data obtained from Computed Tomography (CT) scan to EGSPHANT files. Three CT images set from three lung cancer patients were used in this study. The simulated data were compared with the treatment planning data by using a gamma analysis with selection criteria of 3% dose difference and 3 mm distance-to-agreement. The results show that a good agreement was obtained between the simulated data and the treatment planning data which is indicated by the gamma analysis results of > 95%.

1. Introduction
Radiotherapy is one of the available methods to treat cancer. This method uses a radiation source to kill the cancer cells. Radiotherapy has been known to be the best alternative treatment modality, especially for patients who ineligible for surgery. Besides its non-invasiveness, radiotherapy is preferred due to less time for hospital stay [1]. Radiotherapy can be used to treat many cancer sites in the body, including cancer within thorax cavity such as lung cancer cases. One of the technique commonly used for lung cancer treatment is stereotactic body radiotherapy which is known as SBRT. SBRT uses a large dose in a fewer fraction [2].

In radiotherapy, it is important to know the radiation dose received by the patient to ensure that the prescribed dose specified in the radiotherapy treatment plan is delivered correctly to the patient [3]. If the delivered radiation is smaller the planned dose, the goal to eradicate the cancer cells would not be achieved. On the other hand, if the delivered dose is higher than the planned dose, it could cause unwanted radiation damage to the targeted tissues or organ [4]. Therefore, during verification of the radiotherapy treatment plan, the planner will check whether the designed treatment beams have achieved the prescribed dose or not.

Measuring the dose received by the patient body is difficult to perform. Although it is possible to do so, the technique would cause discomfort and pain for the patients due to an insertion of radiation detectors in the patient body. As an alternative, Monte Carlo technique could be used to estimate the...
radiation dose distribution within the patient body [5]. This method is based on computer computation, where the dose deposition in the medium is calculated by randomly sampling the interaction between radiation sources and absorbing medium [6, 7]. However, the calculation of the dose in the body which consists of complex arrangement of different tissues causes the simulation becomes not simple as that in the homogenous medium such as water medium.

This paper presents a work in estimating the radiation dose distribution within the thorax region, especially for the lung cancer case by using Monte Carlo simulation.

2. Methods and Materials

2.1. Treatment plans

Three lung cancer treatment plans were used in this work. The dose delivery technique selected for these treatment plans were for three-dimensional conformal radiation therapy (3DCRT) technique. There are 10 beams in each treatment plan, combining coplanar and non-coplanar beams. The advantage of this arrangement is the treatment field closely shapes the target tumor and the high dose is focused in the center of the target.

Treatment plan information such as CT image data set, outlined structures of the plans both for the tumor volume, and organ at risks, all beam information including beam energy, beam number, beam orientation and beam meter set were extracted from the treatment plan. This extraction was aided using scripts written in MATLAB (MathWorks). The tumour volume outlined in the plan were Internal Treatment Volume (ITV) and Planning Tumor Volume (PTV) while the outlined organ at risks were combined lung (right and left lung), chest wall and rib.

2.2. Monte Carlo simulation

The simulation was performed using EGSnrc/BEAMnrc Monte Carlo codes and DOSXYZnrc codes. This codes were used to simulate the radiation transport within the linear accelerator head and the dose deposition in the thorax region, respectively [8,9]. For BEAMnrc simulation, BEAMnrc input files were generated by firstly defined and validated the linear accelerator model. The output from the BEAMnrc simulation is the phase space file which provides information about particle histories such as type of particle, its energy and its location.

The DOSXYZnrc simulation requires particle information generated in the previous simulation to calculate the dose deposited by the particle in the absorbing medium. In this case, the absorbing medium is the body tissues in the thorax cavity, especially lung organ. The DOSXYZnrc input files were created based on CT image data set and beam arrangement. The patient geometry were modelled by creating EGSPHANT files based on the CT image data set. In this work, four different materials were used to build EGSPHANT files, consisting of air, lung, soft tissue and bone tissue. The density and the material were specified in pegs4dat files. The beam orientation was defined relative to the CT image coordination system.

The simulation parameters were defined prior to the simulation, which include the number of particle used in the simulation, the selection of variance reduction technique and the electron step algorithm. The number of particle simulated in the BEAMnrc simulation is about $10^8$ particle histories, and about $10^9$ particle histories were simulated in the DOSXYZnrc simulation. The variance reduction technique used was directional bremsstrahlung splitting, while the electron-step algorithm selected was PRESTA-II. The output from the DOSXYZnrc simulation was 3ddose file from each beam. The combination of 3ddose file for each plan was obtained by summing ten 3ddose files which is associated with ten beams.

Since the dose computed by the Monte Carlo is in the unit of Gy per simulated particle, this unit was converted into Gy per monitor unit to be compared directly with the treatment planning system computed dose. This dose conversion was obtained by performing absolute dose calibration for the dose computed from Monte Carlo simulation. This calibration was performed for the 10.4 cm x 10.4 cm field at a homogenous water phantom. The dose at 10 cm depth at central axis was calibrated to 0.01 Gy per monitor unit.
2.3. Analysis of simulated dose distributions

The analysis of the simulated dose distributions were performed using CERR software [10]. The simulated dose distributions were compared with the planned dose distributed computed in the treatment planning system. Both of simulated and planned dose distributions were imported to the CERR. The gamma analysis were employed to compare those dose distribution by using selection criteria of 3% dose difference and 3 mm distance-to-agreement. Only dose points larger than 10% of its maximum dose that were included in the gamma analysis [11]. The gamma analysis was also performed for tightened criteria of 2% dose difference and 2 mm distance-to-agreement.

3. Results and Discussion

3.1. Gamma Analysis

The results of the gamma analysis for the selection criteria of 3% dose difference and 3 mm distance-to-agreement is presented in Table 1. It is showed that the dose points passed the selection criteria from three treatment plans are > 95% for the PTV, combined lung minus ITV, chest wall and rib. It indicates that the simulated dose distribution has a good agreement with the planned dose distribution. In the clinical practice, the common selection criteria to accept the treatment plan are 3% dose difference and 3 mm distance-to-agreement.

| Treatment plans | PTV volume (cm³) | Gamma analysis 3%, 3 mm |
|-----------------|------------------|--------------------------|
| 1               | 36.05            | 99.96                    |
| 2               | 79.85            | 97.12                    |
| 3               | 18.48            | 100                      |

Table 1. The results of gamma analysis of lung treatment plans using criteria 3%, 3 mm

To observe the accuracy of Monte Carlo simulation, the selection criteria were tightened to 2% dose difference and 2 mm distance-to-agreement. The results of the gamma analysis with the tightened criteria is given in Table 2. It is shown that the dose points that passed the criteria for all outlined structures mentioned in Table 2 decrease after tightening the passing criteria from 3%, 3 mm to 2%, 2 mm. The greatest decrease was observed in plan 2, especially for the PTV structure and rib structure. The reason is this plan have the largest PTV volume, then the related tumor size compare to the other plans. The peripheral region of the tumor that adjacent to the lung tissue is subject to a difference when calculated using Monte Carlo simulation. This is because the tumor and the lung tissue has a large density difference, causing less accuracy when calculated using treatment planning algorithm. In this region, Monte Carlo has shown to be more accurate.

| Treatment plans | PTV volume (cm³) | Gamma analysis 2%, 2 mm |
|-----------------|------------------|--------------------------|
| 1               | 36.05            | 89.93                    |
| 2               | 79.85            | 88.73                    |
| 3               | 18.48            | 97.59                    |

Table 2. The results of gamma analysis of lung treatment plans using criteria 2%, 2 mm

Table 3 shows the PTV coverage of the prescribed dose (54 Gy) between the planned dose distribution and the simulated dose distribution. It is shown that for plan 1 and plan 3, the simulation overestimated the PTV coverage of the prescribed dose. However, for plan 2, where the PTV volume is the largest than other plan, the simulation underestimated the PTV coverage. Figure 1 shows the
radiation dose distribution of three lung cancer treatment plans between the treatment planning system and Monte Carlo simulation.

Table 3. PTV coverage of the prescribed dose between the planned and simulated dose distribution

| Plan | Planned dose distribution | Simulated dose distribution |
|------|--------------------------|-----------------------------|
| 1    | 94.72                    | 96.94                       |
| 2    | 94.16                    | 92.80                       |
| 3    | 94.85                    | 95.25                       |

Figure 1. Radiation dose distribution of three lung cancer treatment plan between the planned dose distribution (left) and the simulated dose distribution (right). The red isodose line shows the outlined PTV structure.

The results of gamma analysis for plan 2 and plan 3 are shown in Figure 2. It is shown that the difference between the planned and the simulated dose distribution is higher at the interface between chest wall and lung tissue, especially the rib bones and lung tissue. It is indicated by yellow to reddish color in Figure 2, which represented high dose point difference.
4. Conclusion

This work has modelled the radiation dose distribution within the thorax region from lung cancer treatment plans using Monte Carlo package codes. In comparison to the planned dose distribution, the simulated dose distributions show a good agreement which is indicated by the results of gamma analysis of larger than 95% for PTV structures and organ at risks outlined in the plan (combined lung minus ITV, chest wall and rib) when using a selection criteria of 3% dose difference, 3 mm distance-to-agreement. Tightening the criteria to 2% dose difference, 2 mm distance-to-agreement reducing the dose points that passed the selection, with the largest decrease occurs in the plan with the largest PTV size. The difference is observed in the interface between the chest wall and lung tissue.

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