Dosimetric comparison between different radiotherapy protocols for prostate cancer using Geant4 Monte Carlo simulation

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Abstract. We aimed to evaluate absorbed doses received by organs at risk (OARs) following prostate treatment with external beam radiotherapy (EBRT), using different techniques (3D-CRT and box), number of fields (4 and 6 fields) and photon energies (6 and 10 MV). The MIRD5 adult male anthropomorphic phantom in GEANT4 package was used. However, the prostate, rectum and both femoral heads were not available, hence, were created within the phantom. A dose of 75 Gy was prescribed to the prostate, in all simulated treatments. Field size of 6.4 × 5.9 cm^2 was used in all techniques. For 3D-CRT technique, beams with similar shape to the prostate were used, while for box technique, square-shaped beams were used. Absorbed doses to OARs (rectum, urinary bladder and both femoral heads) were then evaluated. The 3D-CRT technique resulted in lower dose to OARs compared to box technique. Also, the findings show an inverse relationship between number of fields and the OARs doses. There was no dose difference between the OARs with different beam energies. In conclusion, the 6-field 3D-CRT technique with 6 MV photon beam is an ideal treatment option for prostate cancer.

1. Introduction
Prostate cancer is the most common malignancy among males worldwide [1] and the 2nd leading cause of cancer death among males in the United States [1]. In Malaysia, prostate cancer is the 5th most common cancers among males [2]. It was reported that 103,507 new cancer cases were diagnosed in Malaysia from 2007 to 2011, where 6.7% was of prostate cancer.

External beam radiotherapy (EBRT) is a common treatment for prostate cancer. It is preferred due to its non-invasive feature and ability to spare the small bowel (anteriorly) and rectum (posteriorly). Also, by combining EBRT with other treatments (adjuvant therapy), e.g. surgery or chemotherapy, allows the treatment to be more effective. Conventional and conformal EBRT are still commonly performed these days despite the emergence of advanced modalities, i.e. intensity-modulated radiotherapy (IMRT), image-guided radiotherapy (IGRT) and brachytherapy. Moreover, these advanced modalities may not be available in most centers, due to financial and expertise limitations.

The main concern in EBRT is the deposition of unnecessary dose to organs at risk (OARs). In general, direct dose measurements to prostate and OARs (urinary bladder, rectum, and femoral heads) are impossible, without involving invasive procedure [3]. Treatment planning system (TPS) has been widely used to estimate the dose prior to EBRT. However, TPS only provides the dosimetric information of a specific patient, rather than representing the population. Thus, Monte Carlo (MC) simulation on a standard phantom can be used for dosimetric comparison between different EBRT protocols.
MC has been known useful for various applications, spanning from calculations of fundamental problems to simulation of specific radiation treatments [4]. It can be considered as one of the reliable methods for patient dose calculations in radiotherapy [5]. The advancement of computational systems offers the opportunity for MC usage in clinical setting. Geant4 is one of the newest MC toolkits for simulating the passage of particles and photon through matter. It provides accurate probability of radiation events, suitable for medical physics applications [3].

2. Methodology

2.1. The MIRD5 phantom

The ‘human_phantom’ advanced example available in Geant4 version 10.0.0.p03 [6], [7] was used. A 70 kg, 174 cm tall adult male phantom based on MIRD Pamphlet 5 [8] was selected. The prostate was initially absent in the phantom, hence, an oval with a volume of 35 cm$^3$ was added to represent an enlarged malignant prostate [9]. The prostate was positioned inferior to urinary bladder. Initially, the rectum, sigmoid colon and descending colon were present as a combined unit denoted as ‘lower large intestine (LLI)’. However in this study, the rectum was separated from the LLI, by creating a 70 cm$^3$ cylinder, and located posterior to the prostate [10]. The left and right femoral heads were constructed by creating two ovals, each with a volume of 38 cm$^3$, at the medial proximal end of each femur [7].

![Figure 1. The (a) lateral and (b) frontal views of the MIRD5 phantom’s pelvic showing the prostate & OARs.](image)

2.2. Beam geometry

Considering previous literatures [12], [13], [14], 6 treatment plans were created, i.e. 4-field box technique, 4-field three-dimensional conformal radiotherapy (3D-CRT) and 6-field 3D-CRT, each with photon energies of 6 and 10 MV. The clinical tumor volume was kept constant for all plans, i.e. at 2 cm from the margin of gross tumor volume. The weight of each beam was kept at 1:1, in all the techniques used. Source to axis distance technique was used throughout the simulations.

![Figure 2. Antero-inferior views of (a) 4-field box, (b) 4-field 3D-CRT and (c) 6-field 3D-CRT techniques.](image)

2.2.1. 4-field box. Four square-shaped open field beams with field size of 6.4 × 5.9 cm$^2$ were used. The beam angles were set to $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$, as shown in Figure 2 (a).
2.2.2. 4-field 3D-CRT. Four oval-shaped beams that conform to the shape of the prostate were used, with field size of 6.4 × 5.9 cm$^2$, and beam angles of 0°, 90°, 180° and 270° (as shown in Figure 2 (b)).

2.2.3. 6-field 3D-CRT. Six beams with shape and size similar to Subsection 2.2.2 were used, with beam angles of 0°, 45°, 135°, 180°, 225° and 315°, as shown in Figure 2 (c).

2.3. Geant4 Monte Carlo Simulation

For each technique, a pilot run with 10$^7$ histories were generated and repeated 3 times to obtain a standard deviation of <1 % to prostate. Mean energy (MeV) deposited to prostate was converted to Joules (J) and divided by mass (kg) to get the absorbed dose (Gy). A cross multiplication was done to obtain the number of histories correspond to 75 Gy to prostate. Using this value, the simulations were performed again for 3 times and absorbed doses to OARs were recorded.

2.3.1. Treatment techniques versus absorbed dose. Effects of different techniques (3D-CRT and box) using 4-field arrangement and 6 MV photon beams were investigated. Prescribed dose to prostate was fixed to 75 Gy. After the simulations, absorbed doses to OARs from these techniques were compared.

2.3.2. Number of fields versus absorbed dose. Effects of different number of fields (4 and 6 fields) using 3D-CRT and 6 MV photon beams were investigated. Prescribed dose to prostate was fixed to 75 Gy. After the simulations, absorbed doses to OARs from different number of fields were compared.

2.3.3. Beam energies versus absorbed dose. Effects of different beam energies (6 and 10 MV) were investigated by repeating the simulations in Subsection 2.3.1 and 2.3.2 using 10 MV photon beams.

3. Results and Discussions

3.1. Effects of different treatment techniques on absorbed dose

Doses to OARs (75 Gy to prostate) for box and 3D-CRT (both using 4 fields and 6 MV) are shown in Figure 3. All OARs doses from box technique were greater than 3D-CRT. Rectum received the highest dose, i.e. 34.90 ± 0.06 Gy and 28.20 ± 0.03 Gy, for box and 3D-CRT, respectively. Lowest doses were recorded by femoral heads, i.e. on average of 3.70 ± 0.02 Gy and 1.60 ± 0.01 Gy, for box and 3D-CRT, respectively. Largest dose difference was recorded by urinary bladder, i.e. 12.00 ± 0.04 Gy and 4.30 ± 0.01 Gy, for box and 3D-CRT, respectively, where the former resulted in dose almost thrice larger than the latter. This may be due to the bladder position that is very near to the prostate. Thus, a slight increase in beam margin resulted in significant increase in bladder dose. These were in parallel with a study [13], which found that whole pelvic 3D-CRT resulted in significant reductions in doses to rectum and bladder.

![Figure 3. Doses to OARs for different treatment techniques, number of fields and beam energies, for prescribed dose to prostate of 75 Gy](image-url)
3.2. Effects of different number of fields on absorbed dose

Doses to OARs (75 Gy to prostate) for 4 and 6 fields (both using 3D-CRT and 6 MV) are shown in Figure 3. The 6-field technique resulted in lower rectal dose (23.00 ± 0.04 Gy) compared to 4-field (28.20 ± 0.00 Gy). This may be due to lower beam weight (carried by each beam) with higher number of fields, which resulted in better tumor dose distribution and lesser OARs doses. For urinary bladder, only a slight dose difference (0.20 ± 0.00 Gy) was recorded between the fields. For femoral heads, the results were the opposite, where doses using 6-field were significantly higher. This may be due to beam arrangements at 45°, 135°, 225° and 315°, which may have slightly intercepted with the femoral heads. This finding is supported by an earlier study [15], which mentioned that with increased number of fields, the rectum can always be spared, however at the expense of increased dose to femoral heads.

3.3. Effects of different beam energies on absorbed dose

Doses to OARs (75 Gy to prostate) for 6 and 10 MV photon beams are shown in Figure 3. Theoretically, higher energy photon should have greater penetration (less energy deposition) in tissues compared to lower energy, and thus, allows better tissue sparing for OARs. However, in this study, there was no significant dose difference found between different beam energies. This is supported by a study, which suggested that selection of beam energy in multi-fields technique is not necessary [16].

4. Conclusion

In the absence of advanced modalities, the 6-field 3D-CRT technique using 6 MV photon beam can be considered as an ideal option for prostate cancer, as doses to rectum and urinary bladder can be significantly reduced. Although the doses to both femoral heads were slightly higher compared to the other OARs, these can still be improved by adjusting the angle, field size and weight of each beam.

5. References

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