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AN AUTOMATED DOSE VERIFICATION TOOL FOR PROTON THERAPY PLANS USING GEANT4/TOPAS*

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Abstract

Proton therapy has become a significant treatment option for many tumors. In commercial treatment planning systems (TPS), the computationally efficient pencil-beam (PB) analytical algorithm is frequently utilized for dose calculation. Due to the PB algorithm's limited accuracy, a higher accuracy dose verification tool is a legal requirement for proton therapy. Therefore, we developed an automated treatment plan dose verification framework based on the Monte-Carlo (MC) algorithm.The MC beam model, including the phase space, energy spectrum, and the number of protons per MU, was derived from commissioning data and fed into our automated software. CT and treatment plan from TPS were input for the automated software. The developed tool was validated and compared with the PB algorithm of Pinnacle3 TPS for 85 prostate patients.The difference between the PB dose and the MC dose of our automated tool was evaluated using gamma analysis (3 mm/3%, and 2 mm/2% criteria) and mean absolute errors. Although the result shows good agreement and the passing rate was about 95%, the difference of all the indices was found to increase as the degree of tissue heterogeneity increased. The MC dose has a higher MAE in CTV, and femoral head compared to the PB dose.An automated framework can quickly calculate the MC dose with high accuracy among different cases. The automated software can facilitate patient plan verification in institutions and be useful for other clinical applications.

INTRODUCTION

Due to its Bragg peak characteristic, proton radiotherapy has increased clinical use in the last decade [1]. It has more homogeneous, conformal, and normal sparing than conventional photon radiotherapy. The actual dose distribution may differ from the planned dose because of the existence of uncertainties such as dose calculation uncertainties, anatomy changes, and so on [2]. Therefore, providing accurate dose calculation tools is essential for treatment planning and plan quality assurance.

Due to its high computation speed, the pencil beam (PB) analytic algorithm is widely used in commercial treatment planning systems (TPS). It uses the water-equivalent thickness longitudinally and assumes that the material on the central axis is laterally homogeneous [3]. Particularly in inhomogeneous tissues, the approximation of multiple Coulomb and nuclear reactions in the PB algorithm leads to dose discrepancy and range uncertainties [4]. The Monte-Carlo methods, regarded as the gold standard for dose calculation in radiotherapy, simulate physics interactions by many random sampling cross-sectional interactions [5]. Thus, developing the MC dose recalculation tool for post-planning dose verification is necessary for hospitals.

This study aims to build an automated MC dose recalculation framework for proton therapy treatment plans. Additionally, we compared it with the PB algorithm in prostate cancers. The dose discrepancy was evaluated using the gamma analysis method (3 mm/3% and 2 mm/2%). The mean absolute error between the MC dose and PB dose also was calculated to evaluate the dose discrepancy.

METHOD AND MATERIAL

An automated MC re-calculation framework was developed for dose checking of treatment plans. Figure 1. shows the workflow of the proposed tool. The Geant4-based TOPAS toolkit was used in our study [6]. The default physics list contains G4EMStandardPhysics_option4, HadronPhysics-QGSP_BIC_HIP, G4DecayPhysics, G4IonBinaryCascade Physics, G4HadronElasticPhyscisHP, and G4Stopping Physics. The IMPT plans were optimized in the Pinnacle3 TPS, v15.0 (Philips Healthcare, Fitchburg, WI, USA) and calculated by the PB algorithm. The DICOM data (CT, RS, and RN) were exported from TPS and then fed into our tool. After the simulation, the dose calculated by the MC tool was compared with that of the PB algorithm.

Beam Modeling

The beam data library (BDL), which contains beam parameters for various energies, is implemented in TOPAS as a look-up table. These parameters must be tuned to align the Monte-Carlo simulation with experimental measurement. The BDL includes three sections: energy spread, phase space, and the number of protons per MU.

- Energy spread: the energy distribution of proton beams is a Gaussian distribution with a mean and standard deviation.

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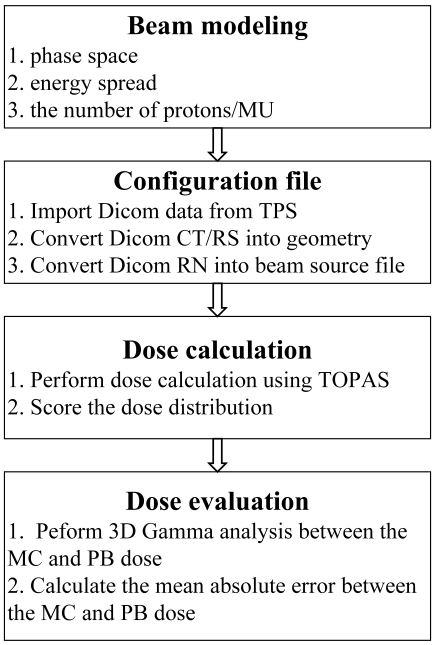

Figure 1: The workflow of our automated Monte-Carlo dose calculation tools.

- Phase space: phase space parameters are determined as a function of energy at the nozzle output, such as spot sizes and beam divergences
- The number of protons per MU For each nominal energy was calibrated.

Patient Data

In our study, 85 cases of prostate cancer were used. An institutional review board-approved protocol for retrospective data collecting included all patients. The beam angle was set at 90° and 270°, and all of the patient's plans were optimized using the multi-field optimization technique. The planning target volume (PTV), clinical target volume (CTV), bladder, rectum, left femoral head, and the right femoral head was contoured by radiation oncologists.

Dose Comparison

The 3D dose distribution calculated by the MC algorithm was compared to that of the PB algorithm. The difference was assessed using the mean absolute error between the PB dose and the MC dose. The 3D gamma index analysis (using 3%/3 mm and 2%/2mm criteria) was also used to evaluate the difference.

RESULT

Figure 2. shows the PB dose, MC dose distribution, their difference map, and DVH plots. While their DVH and dose distribution were comparable, there was a dose discrepancy in the high dose-gradient region. Additionally, the CTV, Bladder, and femoral head of the DVH in the Monte-Carlo method changed significantly from those in the PB algorithm.

The MAE between the MC dose and the PB dose was calculated and presented in Table 1. The MC dose had a higher MAE in CTV, and femoral head compared to the rectum and bladder. This also demonstrated that the PB dose has more calculation uncertainties in the complex tissue. Table 2 shows the gamma analysis result between the MC dose and the PB dose. Among the 85 prostate patients, the average gamma passing rate (2 mm/2% criteria) was about 96.7%.

Table 1: The mean absolute error relative to the maximum dose value between the MC dose and PB dose among 85 prostate cases, shown as mean ± standard deviation.

	MC dose – PB dose
CTV	3.74 % ±1.21 %
Bladder	1.01 % ±0.66 %
Rectum	0.84 % ±0.36 %
Left femoral head	1.38 % ±0.26 %
Right femoral head	1.31 % ±0.32 %

Table 2: The gamma passing rate (3 mm/3% and 2 mm/2% criteria) result between the MC dose and PB dose among 85 prostate cases, shown as mean ± standard deviation.

Criteria	**MC dose – PB dose**
3mm/3%	98.88 % ±0.92 %
2mm/2%	96.76 % ±1.95 %

DISCUSSION

In our study, the MC-based dose re-calculation tool was developed for dose checking in clinical. We compared the MC dose with the PB dose, showing a relatively significant difference in high-dose-gradient regions. Without an in-depth understanding of command line deployment, and function dependencies, clinical users can employ this tool and integrate it into commercial TPS. Excerpt for the physics dose, this tool also can calculate the dose-to-water, linear energy transfer, and dose deposited by another particle radiotherapy.

However, the huge calculation time is a significant problem for employing the tools in treatment plan optimization. It takes about 10 hours (compared to minutes for the analytical calculation within the TPS) to calculate a patient plan dose. Recent MC simulation studies have focused on improving MC calculation speed by simplifying the physics process and deploying parallel computing.

CONCLUSION

In summary, we developed an automated MC dose re-calculation tool. It is a crucial tool for the dose verification and quality control of treatment plans. Additionally, the automated tool can easily be implemented in other institutions and be useful for other clinical applications.

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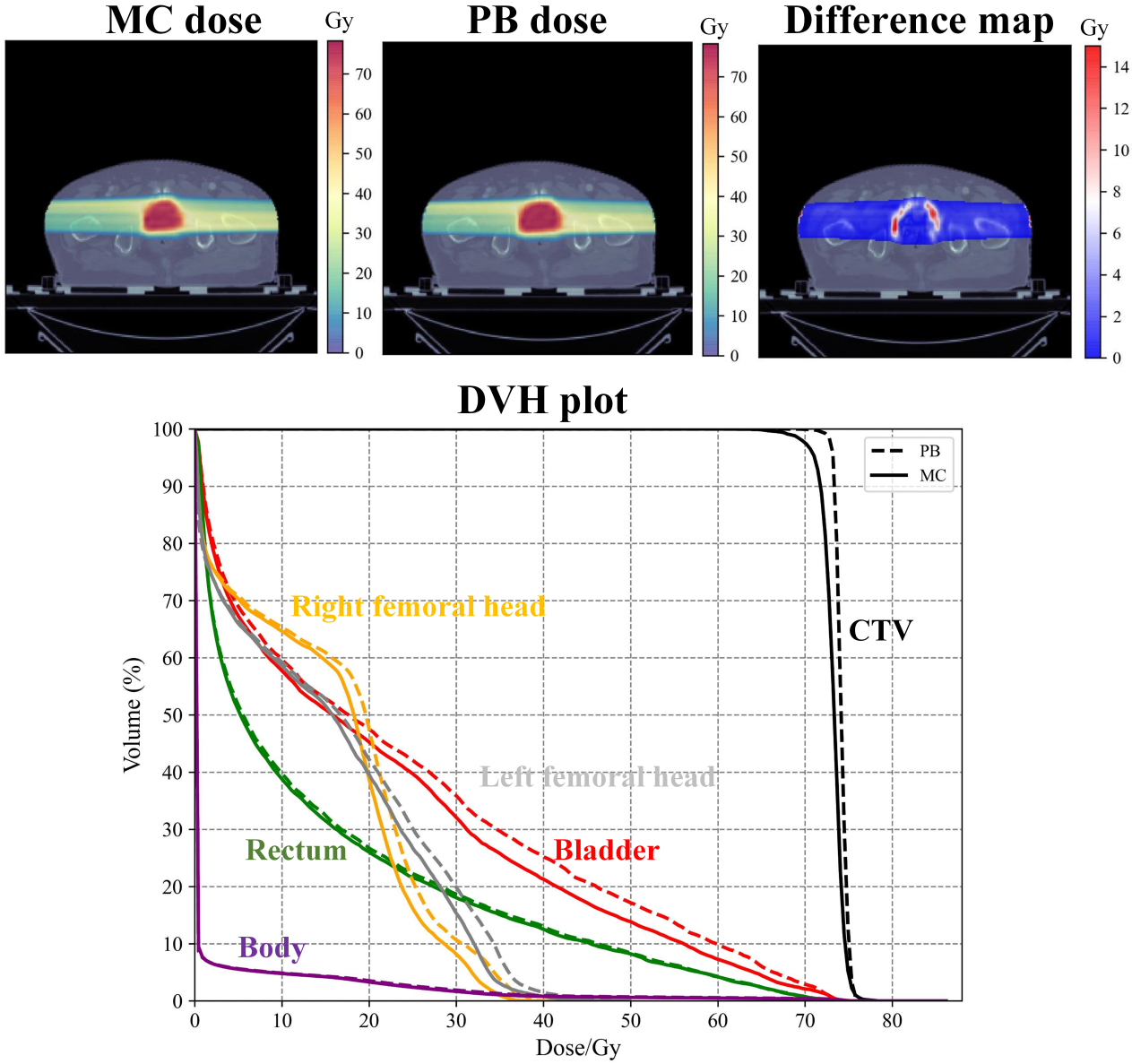

Figure 2: The dose result of the PB algorithm and MC algorithm, the dose difference map between the PB dose and the MC dose, and the DVH plots of the PB dose and MC dose.

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