ORIGINAL ARTICLE

Eastern Journal of Medicine
East J Med 30(1): 76-81, 2025
DOI: 10.5505/ejm.2025.14306

Comparative Analysis of Percentage Depth Dose Calculations by Radiotherapy Treatment Planning System Algorithms in Non-Homogeneous Media

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ABSTRACT

This study aims to investigate the dose distributions produced by three treatment planning systems (TPSs) across various mediums by constructing a phantom that simulates a mediastinal environment.
Materials and Methods: We utilized Computerized Tomography (CT) to scan a phantom with bone, PMMA, and lung blocks. It was subsequently moved to Eclipse™ TPS. In Eclipse TPS, we utilized a 6 MV photon beam with a Source Skin Distance of 100 cm and a field size of 20x20 cm2. We obtained the percentage depth doses (PDD) by recording the dose at 3 mm intervals from the center of each block to the desired depths. These processes were repeated for the other two TPSs. We observed that the PDD acquired from bone, PMMA, and lung blocks in Eclipse TPS using the PBC algorithm revealed a significant contrast in the bone block, which increased as we move away from the build-up area. Subsequently PDD values from the lung medium are compared. Eclipse and Prowess TPS values were found to be similar, while Monaco TPS, utilizing the Monte Carlo Algorithm, demonstrated significant difference. Although Monaco TPS recorded higher PDD values compared to the other two TPSs both before and after the build-up region, it maintained a consistent level in the build-up region and yielded slightly lower doses than the other TPSs.
The behaviors of TPSs employed in commercial radiotherapy planning should be calculated in different environments, and compared with the measured values. These differences should be taken into consideration when making treatment decisions.

Keywords: Treatment Planning System, Non-homogeneous environment, Algorithm, PBC, Monte Carlo

Introduction

Treatment planning systems (TPS) are used in radiotherapy to administer the intended dose to the target volume while minimizing the dose to the surrounding critical organs(1). Selection of TPSs using correct treatment dose calculation algorithms is important in order to guarantee the precision of target and critical organ doses (2, 3). The behavior of radiation in environments of different densities is well known from the perspective of radiation physics. The human body is composed of various diverse environments, such as muscles, lungs, bones, teeth and air cavities. Correctly distinguishing between target tissue and healthy tissues reduces error rates in treatment(4). This highlights the critical importance of precisely assessing the energy transfer to the surrounding medium(5). Dose accuracies are related to the assumptions and approaches used by the algorithms. These approaches cause uncertainty in the accuracy of the dose given, especially in organs such as bones and lungs(6, 7). While the effects of primary photons interactions are typically estimated with a high degree of accuracy, the modeling of scattered radiation often lacks precision. Moreover, many texture smoothing algorithms designed for inhomogeneous environments are predominantly applied to homogeneous media with some simple geometric structures(8). According to the recommendations of the International Commission on Radiation Units and Measurements (ICRU), the error rate in the targeted dose should be below 5%(9). Independent verification of monitor unit (MU) and patient dose distributions on linear accelerators (Linacs) have remained essential components of quality control in radiation oncology(10). Some corrections rely on secondary

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Received: 05.09.2024, **Accepted:** 13.01.2025

independent calculations, either manually or with commercially available software. These are measured with reference beam data using a water phantom. However, the calculation accuracy of these verification systems and reference conditions should also be taken into consideration(11).

Modern model-based algorithms like pencil beam convolution (PBC), anisotropic analytical algorithm (AAA), and collapsed cone convolution (CCC) are utilized in three-dimensional TPSs to model the photon beam's initial properties and interaction within the patient (6, 12, 13). In clinical radiotherapy application, plastic phantoms are widely utilized as substitutes for water due to their presumed comparable effectiveness. However, phantoms exhibit slight differences in density and flow properties when compared to water. Monte Carlo (MC) simulations can be utilized to evenly distribute an identical dose within both the human body and a phantom medium (14). MC dose calculation algorithms are accurate due to considering the numerous interacting particles in the calculation process (13). There is actually no mathematical proof for this and not enough evidence that the phantom can completely mimic a patient. It presents two methods to acknowledge the phantom as being equal to a human. One involves changing the patient's anatomy to match the phantom's shape, while the other involves transforming a diverse patient into a uniform setting (14).

Photon energies demonstrate unique characteristics in heterogeneous environments. Regions such as the thorax, characterized by non-homogeneous structures, have been investigated due to their potential to introduce inaccuracies in radiotherapy dose calculations(15). The acceptability criterion for dose calculations along the central axis and TPS calculations in non-homogeneous environments is usually 3-4% (16, 17). However, this asymmetry is not present in areas distant from the location of electronic equilibrium. TPSs utilize algorithms that, although not perfectly precise, are still preferred over not making any corrections to estimate dose in heterogeneous environments (18, 19). The research using such as lung equivalent and water equivalent materials at 18 MV photon energy found that the variation in results from experiments with correction-based algorithm calculations could reach 21% (20). In lung cancer radiotherapy, the variability in the mediastinum region's composition can result in dose discrepancies and uncertainty. In mediastinum-like settings treated with 18 MV photon energy, variations in dose of up to 14% are observed between correction-based algorithm calculations along the central axis and experimental measurements (21). Studies has demonstrated that planar dose measurements utilized with the AAA algorithm of the RapidArc treatment system and the Collapsed Cone Convolution Superposition (CCCS) algorithm of the Helical Tomotherapy system exhibited discrepancies of less than 3% in the central mediastinum region when evaluated using a chest phantom. However, larger deviations of 5% to 8% were identified in regions with low-density inhomogeneities and at the boundaries between water and styrofoam materials[22]. Research in the field has mostly utilized similar environmental differences to evaluate doses and measure them in various settings. Our goal was to analyze dose distributions of three TPSs in various tissues using diverse calculation algorithms, by creating a phantom resembling a mediastinum setting.

Materials and Methods

Our study utilized the PTW inhomogeneity phantom T40020 (Figure 1). This phantom is created to hold three blocks with varying densities within it. We scanned bone, Polymethyl Methacrylate (PMMA), and lung blocks using Toshiba Aquilion (Toshiba Medical Systems, Japan) CT at 120 kV and 2 mm slice thickness. It was subsequently moved to Eclipse™ TPS (Version 8.9.17, Eclipse) using Digital Imaging and Communications in Medicine (DICOM). In Eclipse TPS, our plan was to utilize the 6 MV photon beam from the Siemens Primus Plus linear accelerator with a Source Skin Distance (SSD) of 100 cm and a field size of 20x20 cm^2. In the plan, we utilized a 2.5 mm grid size along with the PBC algorithm. We calculated the percentage depth doses (PDD) by reading the dose point by point at 3 mm intervals from the center of each block to the depth, based on the plan we received, and normalizing the values to the highest dose value. Subsequently, the tomography data from the phantom were transferred to the Prowess Panther system (Version 5.10, California, USA) treatment planning systems. This plan was created using the Siemens Artiste linear accelerator information under identical circumstances as the Eclipse TPS.

Fig. 1. PTW inhomogeneity phantom T40020

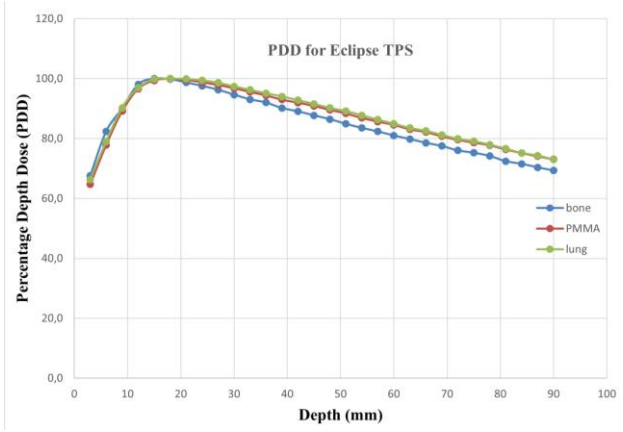

Fig. 2. PDD graphics of three media for Eclipse TPS

Using the Prowess Panther TPS which using CCCS algorithm for dose calculation, we determined PDDs based on the dose distributions obtained beneath each block. Finally, all procedures were repeated utilizing the MC Algorithm from the Monaco (version 6.1.2.0) TPS with a grid size of 2 mm.

Results

Arrangements were prepared on the heterogeneous phantom for three different TPS, with a SSD of 100 cm, a 20x20 cm^2 opening, and utilizing 6 MV photon energy. Depth doses for each region were determined by extracting point dose values at 3 mm intervals from the center of each block to the base of the phantom using the calculated plans of each TPS. The received depth doses were adjusted to the highest dose value and PDD values were obtained for each scenario. We plotted the PDD curves acquired from the various environments merged together (Figure 2, 3, 4). Following an individual examination of the PDDs for each planning, we proceeded to compare the PDDs from each material block axis on a graph (Figure 5, 6, 7). Figure 8 displays the PDD comparison of three TPS in the build-up region for a) bone, b) PMMA, c) lung mediums.

Figure 2 reveals the PDD values obtained from bone, PMMA, and lung blocks in Eclipse TPS using the PBC algorithm, with the most

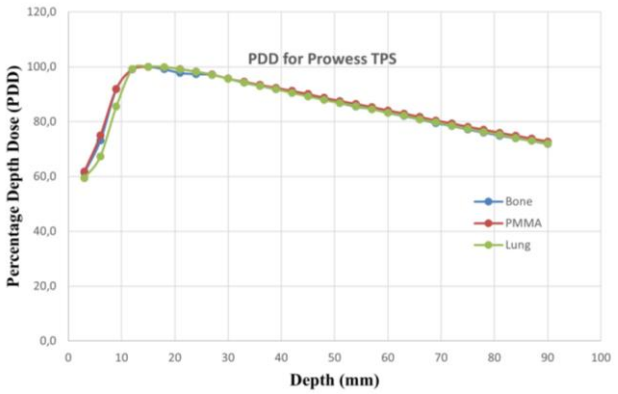

Fig. 3. PDD graphics of three media for Prowess TPS

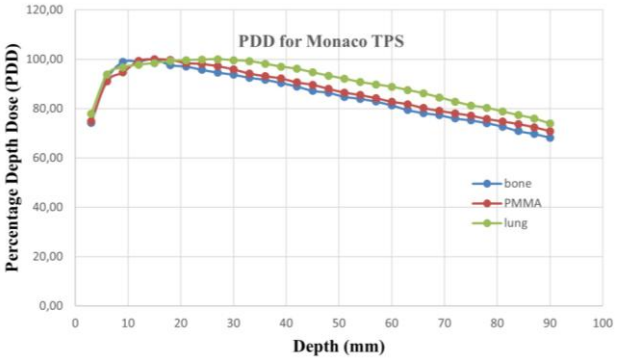

Fig. 4. PDD graphics of three media for Monaco TPS

pronounced differences observed in the bone block, becoming more apparent as the distance from the build-up region increases. Figure 3 demonstrates the PDDs acquired from the dose distributions of Prowess TPS in all three scenarios. In these charts, environmental densities do not have a significant impact on PDDs, with only a decline observed in depth doses until the build-up region for lung medium. Differences can be observed between the blocks towards the build-up region when comparing PDD values obtained from plans created with Monaco TPS which use MC calculation algorithm for three different environments in figure 4. Beyond the accumulation region, the PDD values for the lung block are notably higher than those observed in the other two media. Figure 5 demonstrates PDDs for the bone block from three TPSs with different calculation algorithms, showing notable variations, particularly in the build-up and pre-build-up regions. The Monaco TPS exhibits the most significant increase before the build-up region. Following the construction area, the most noticeable change is observed in the Prowess TPSs, with increased PDDs. Figure 6 displays the PDDs obtained for the PMMA medium from three different TPSs, indicating that the Monaco

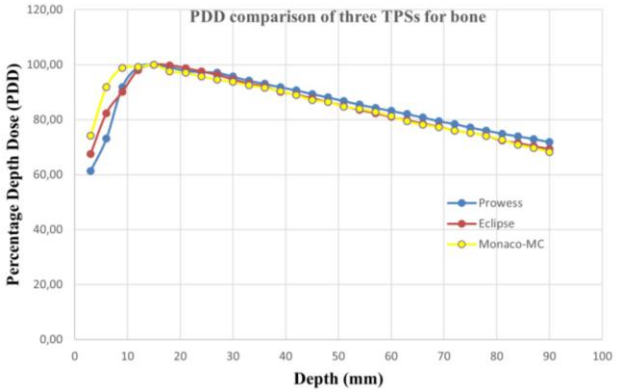

Fig. 5. PDD comparison of three TPSs for bone

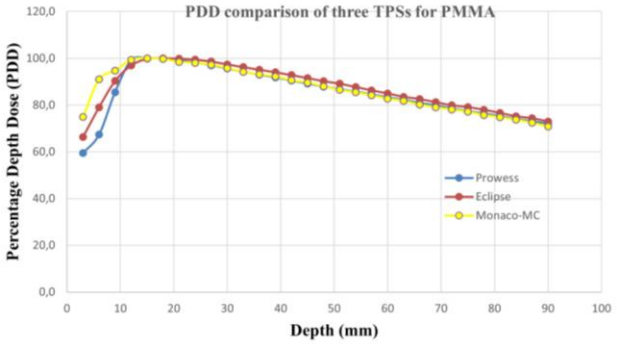

Fig. 6. PDD comparison of three TPSs for PMMA

TPSs have higher PDD values before the build-up region due to the other two TPSs. Following the region of accumulation, the PDD values are similar, whereas the Eclipse TPSs values, utilizing the PBC algorithm, are elevated. In figure 7, the PDD values from the lung medium are compared. Eclipse and Prowess TPS values are similar, while Monaco TPS with MC Algorithm demonstrates significant difference. While the Monaco TPS shows higher PDD values than the other two TPSs both before and after the build-up region, it maintains a consistent level within the build-up region and delivers slightly lower values compared to the other two TPSs.

Discussion

Our study compared the PDD generated by various TPSs employing different algorithms in adjacent non-homogeneous environments. The PDDs produced by various treatment planning dose calculation algorithms were different as anticipated, both internally and compared to each other.

Carrasco and colleagues (23) conducted MC simulations and detector readings in heterogeneous layers with materials simulating

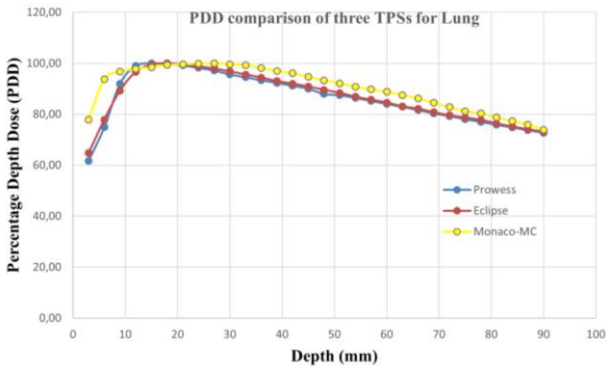

Fig. 7. PDD comparison of three TPSs for lung

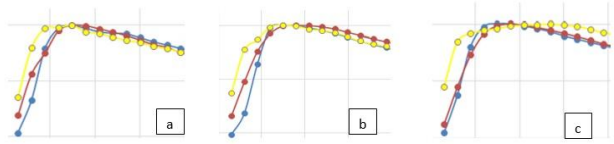

Fig. 8. PDD comparison of three TPS in build-up region for a) bone, b) PMMA, c) lung

water and bone to assess the dose values calculated by two TPS plans using different dose calculation algorithms. While they found that utilizing the heterogeneity correction factor was superior to not using it, they demonstrated that the selection of algorithm was crucial and resulted in notable discrepancies between the expected PDD curves and the simulated ones. They also mentioned that the variances found with materials mimicking lungs were larger than the variances found with materials mimicking bones. Furthermore, they noticed that the conformity between MC simulations and experimental measurements was reliable, given that the general uncertainty in MC was around 2%. In our study, we found that the differences between lung equivalent materials were larger than those between bone equivalent materials.

Hasani et al. (13)simulated the 6-MV Siemens Primus linear accelerator with the MCNPX MC code and compared the results for PDD with the measured data. They compared the algorithms (CCC, Superposition and FFT) of the ISOgray TPS for homogeneous media for the PDD curves and found that the results were consistent with each other. However, when compared with the MC simulation, they found lower doses than expected for all three algorithms in the build-up region (0-1.6 cm) for the TPS algorithms. They observed that the PDD curves shifted slightly to the right and up when going deeper than the build-up region. In our study, when we compare the results obtained from Eclipse TPS using the

PB algorithm and Prowess TPS using the CCCS algorithm with MC-based Monaco TPS for normal tissue-like PMMA material, there was no significant difference for the build-up region, while at deeper depths, the PDD values obtained from the other two TPSs have shifted upwards compared to the PDD values obtained from the MC-based TPS in the same direction of Hasani's study. The variation in the build-up region could be attributed to differences between the simulation material they utilized and the one used in our study. However, when compared to MC, discrepancies may still occur between other algorithms, even in homogeneous environments. Besides this they reported that in non-homogeneous environments such as the lung, the CCC algorithm calculates lower doses than the MC algorithm. Similarly, we observed that in the lung environment before and after the build-up region, the CCCS algorithm calculates lower doses than the MC algorithm.

In a retrospective study conducted by Stephen F. Kry et al. (23) with a thorax phantom, they made treatment plans for 3DCRT and IMRT with MC, Convolution/superposition, AAA and PB and looked at the difference between the measured dose and the calculated dose. As a result, they determined that the calculated dose of algorithms other than MC was higher than the measured dose, and that the MC algorithm was suitable for both 3DCRT and IMRT in accordance with the measured values. As a conclusion, they recommend being more careful in dose calculations for heterogeneous environments due to the higher dose calculated for the lung target by algorithms other than MC. In our study, we observed that dose calculations of different algorithms in different environments such as the lung were different and, in line with their study, PBC and CCCS algorithms had higher PDD values than the MC algorithm in the build-up region for lung material.

In studies conducted to investigate the TPS algorithms, phantoms with different densities defined after a certain depth have been frequently used. In our study, we created treatment plans under the same conditions with three different planning systems using different dose calculation algorithms on a phantom with blocks with different tissue densities on its front surface, used for quality control in radiotherapy. When we compared the dose distributions, we obtained from these blocks positioned side by side as a mediastinum media and starting from the skin and the PDDs we calculated, we observed differences in the PDD curves both within the blocks and after the blocks. The biggest difference occurred on the lung block in Monaca TPS using the MC algorithm. As a result, the behaviors of TPSs used in commercial radiotherapy planning should be calculated in different environments, compared with the measured values, and these differences should be taken into consideration when making treatment decisions.

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