Article published online: 2020-12-31

Mini Symposium - RT DOSIMETRY AND FRACTIONATION: Original Article

Dose prediction accuracy of anisotropic analytical algorithm and pencil beam convolution algorithm beyond high density heterogeneity interface

Suresh B. Rana

Abstract

Purpose: It is well known that photon beam radiation therapy requires dose calculation algorithms.The objective of this study was to measure and assess the ability of pencil beam convolution (PBC) and anisotropic analytical algorithm (AAA) to predict doses beyond high density heterogeneity. **Materials and Methods:** An inhomogeneous phantom of five layers was created in Eclipse planning system (version 8.6.15). Each layer of phantom was assigned in terms of water (first or top), air (second), water (third), bone (fourth), and water (fifth or bottom) medium. Depth doses in water (bottom medium) were calculated for 100 monitor units (MUs) with 6 Megavoltage (MV) photon beam for different field sizes using AAA and PBC with heterogeneity correction. Combinations of solid water, Poly Vinyl Chloride (PVC), and Styrofoam were then manufactured to mimic phantoms and doses for 100 MUs were acquired with cylindrical ionization chamber at selected depths beyond high density heterogeneity interface. The measured and calculated depth doses were then compared. **Results:** AAA's values had better agreement with measurements at all measured depths. Dose overestimation by AAA (up to 5.3%) and by PBC (up to 6.7%) was found to be higher in proximity to the high-density heterogeneity interface, and the dose discrepancies were more pronounced for larger field sizes. The errors in dose estimation by AAA and PBC may be due to improper beam modeling of primary beam attenuation or lateral scatter contributions or combination of both in heterogeneous media that include low and high density materials. **Conclusions:** AAA is more accurate than PBC for dose calculations in treating deep-seated tumor beyond high-density heterogeneity interface.

Key words: Anisotropic analytical algorithm, dose prediction, high density heterogeneity, inhomogeneity corrections, pencil beam convolution

Introduction

External beam radiation therapy (EBRT) is one of the most commonly used methods for cancer treatment in which ionizing radiation is used in an attempt to kill the malignant tumor cells and slow down their growths. It is essential that the prescribed dose be delivered to the tumor with high accuracy. This is because under-dosage may not kill all the cancer cells and over-dosage can harm the surrounding healthy tissue more than necessary, which could lead to unwanted side effects.

During EBRT treatment, the photon beam passes through different tissue densities within the patient's body before it reaches the target. Therefore, beam characteristics along a heterogeneous path will be different and dose calculation algorithms must incorporate heterogeneity corrections.[1,2] American Association of Physicists in Medicine, Task Group 65 (AAPM, TG 65) recognized that properly accounting for tissue heterogeneity "is an essential component of dose optimization and the objective analysis of clinical results, especially with the advent of 3D precision conformal radiotherapy and the extension of IMRT treatments to structures that have not been irradiated before".[2]

Previous studies on the effects of low density inhomogeneities on dose calculations were mostly focused on within lung equivalent materials or near lung/tissue interface or at selected depths beyond the low density inhomogeneity.[3-7] The purpose of this study was to investigate the ability of Pencil Beam Convolution (PBC) algorithm and Anisotropic Analytical Algorithm (AAA) to calculate the dose in deep-seated water equivalent tissue beyond high density heterogeneity interface. The data computed by AAA and PBC were compared against the measurements.

Department of Radiation Oncology, Arizona Center for Cancer Care, Peoria, AZ, USA

Correspondence to: Mr. Suresh B. Rana,
E-mail: suresh.rana@gmail.com

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Quick Response Code:	Website: www.sajc.org
	DOI: 10.4103/2278-330X.105888

Materials and Methods

This study was done in a scenario assuming that tumor is located 20 cm deep inside the human body and 6 MV photon beam travels through soft tissue followed by lung, soft tissue, and rib/bone before reaching the tumor. The dose calculations were performed in the Eclipse treatment planning system (TPS), version 8.6.15 (Varian Medical Systems, Palo Alto, CA).

Depth dose calculations

The phantom A (30 × 30 cm^2, 20 cm deep) and phantom B (30 × 30 cm^2, 30 cm deep) were created as 3D CT

structure sets in the Eclipse TPS. Each phantom was defined as the body structure (CT number = 0) in order to calculate the dose. Before the dose computation, rectangular slabs (30 × 30 cm^2) of solid water (density = 1.0 g/cm^3), Poly Vinyl Chloride (PVC) (density = 1.6 g/cm^3), and Styrofoam (density = 1.2 × 10^{-3} g/cm^3) were scanned using GE Light Speed CT Scanner and their CT numbers were confirmed equivalent to water, bone, and air, respectively. The phantoms' layers consisting of solid water, Styrofoam and PVC were assigned with CT numbers of 0, -990 and + 1200, respectively. All dose calculations in this study utilized 6 MV photon beam of Varian Trilogy linear accelerator (Varian Medical Systems, Palo Alto, CA) and source to surface distance (SSD) was set to 100 cm [Figure 1]. Furthermore, the dose for 100 Monitor Units (MUs) was calculated by AAA and PBC and 2.5 mm calculation grid size was used for all cases.

First, depth doses at an interval of 1 cm along the central axis of homogeneous medium (phantom A) were calculated for field size 10 × 10 cm^2. Second, for heterogeneous media (phantom B), dose calculations were done for 5 × 5, 10 × 10, and 20 × 20 cm^2 field sizes. Three points (P1, P2, and P3) were identified as points of interest in the water region and these points are labeled in Figure 1. The reason for selecting these three points was to investigate if the discrepancies between the measured and calculated doses were consistent at P1 (1 cm from PVC–water interface), P2 (2 cm from PVC–water interface), and P3 (3 cm from PVC–water interface). All calculated (AAA and PBC) doses were normalized to the depth of maximum (dmax) dose.

Depth dose measurements

The central axis depth dose data were measured using Exradin A1 cylindrical ionization chamber (Standard Imaging, Middletown, WI) at selected depths in both phantoms for 100 MUs of 6 MV photon beam from Varian Trilogy linear accelerator, and 100 cm SSD was used for all measurements. First, solid water blocks of 30 × 30 × 20 cm^3 dimensions were used and measurements were done at an interval of 1 cm up to 19 cm depth for field size 10 × 10 cm^2. Second, in order to simulate the inhomogeneous phantom B, rectangular slabs (30 × 30 cm^2) of solid water, PVC, and Styrofoam were arranged as shown in Figure 1. The measurements were done at P1, P2, and P3 along the central beam axis for field sizes 5 × 5, 10 × 10, and 20 × 20 cm^2.

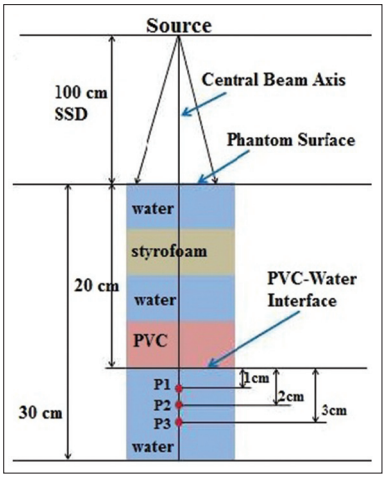

Figure 1: A schematic of the experimental setup for depth dose computations and measurements in inhomogeneous phantom B, The central axis percent depth doses were compared at points of interest P1, P2, and P3 which are 1, 2, and 3 cm from the Poly Vinyl Chloride -water interface, respectively

For both phantoms, the average ($R_{avg.}$) of two electrometer readings (nC) at the selected depths was recorded. Then, R_{avg} was converted to the depth dose ($Dose_{Depth\ X}$) using equation (1).

$$Dose_{Depth\ X} = \left(\frac{100}{R_{avg@1.5cm}}\right) \times R_{avg.@\ Depth\ X} \quad (1)$$

where, Depth X is a depth at *X* cm along the central axis of the phantom.

All measured doses were normalized to known dose at the dmax of 1.5 cm, and the measured percent depth doses were compared against the calculated percent depth doses (AAA and PBC).

Results

The benchmark test for the cylindrical ionization chamber using the central axis percent depth dose comparison in homogenous medium is shown in the Figure 2. The agreement between the measured and calculated (AAA and PBC) doses was obtained within ± 1%. This test confirmed that the cylindrical ionization chamber could be used for measurements in inhomogeneous phantom B.

Table 1 shows the percent depth dose data and the percent difference between the measured and calculated data for selected measurement points in phantom B. The AAA's values had better agreement with the measurements at all three points of interest (P1, P2, and P3) than that of PBC, and this was true for all three test field sizes. However, at the given point of interest, the discrepancy between calculated (AAA and PBC) and measured doses was dependent on the field size. For example, at P1, the percent dose differences increased from 1.5 to 5.3 for AAA and from 3.7 to 6.7 for PBC as the field size increased from 5 × 5 cm^2 to 20 × 20 cm^2. This trend of increased percent dose difference as a function of field size was observed at P2 and P3 as well [Table 1 and Figure 3]. The three measurement points receive lateral scatter from the PVC and solid water materials placed above them and there is a lateral scatter loss in the air region too. Thus, improper beam modeling within algorithms while accounting scatter contribution to the measurement points may have contributed to these dose discrepancies.

For a given field size, both algorithms exhibited maximum (AAA: Range, 1.5-5.3% and PBC: Range, 3.7-6.7%) and minimum (AAA: Range, 0.1-3.6% and

Table 1: The measured and calculated (Anisotropic analytical algorithm and Pencil beam convolution) central axis percent depth doses at P1, P2, and P3 beyond high density heterogeneity interface for field sizes 5 × 5, 10 × 10, and 20 × 20 cm² (top to bottom) are compared. P1, P2, and P3 are points of interest at depths of 21, 22, and 23 cm, respectively in phantom B [Figure 1]. The measured as well as calculated doses were normalized to the dose of maximum (dmax) reading obtained at 1.5 cm depth. (6 MV photon beam, 100 cm source to surface distance to the surface of phantom)

	Measurement	AAA		PBC	
	Dose (%)	Dose (%)	Δ (%)	Dose (%)	Δ %
Field size 5×5 cm²					
P1	35.6	36.1	1.5	36.9	3.7
P2	33.7	33.9	0.6	34.6	2.7
P3	31.8	31.9	0.3	32.5	2.2
Field size 10×10 cm²					
P1	38.7	40.0	3.4	40.8	5.4
P2	37.0	37.6	1.6	38.4	3.8
P3	35.2	35.5	0.9	36.3	3.1
Field size 20×20 cm²					
P1	42.0	44.2	5.3	44.8	6.7
P2	39.8	41.6	4.5	42.6	6.3
P3	38.1	39.5	3.7	40.3	5.8

AAA=Anisotropic analytical algorithm, PBC=Pencil beam convolution algorithm

$$\Delta \text{ or Difference (\%)} = \frac{\text{Calculated (AAA or PBC) Percent Depth Dose} - \text{Measured Percent Depth Dose}}{\text{Measured Percent Depth Dose}} \times 100$$

PBC: Range, 1.9-5.7%) dose discrepancies at P1 and P3, respectively. The dose discrepancies were more pronounced as the measurement point was closer to the high-density heterogeneity interface [Figure 3]. As the photon beam is hardened when it traverses high density medium (PVC), the removal of low energy photons from the photon beam causes increased number of ionizations in the PVC, and this phenomenon leads to increase in the depth dose downstream. Thus, higher dose overestimation at P1 was probably due to improper modeling of the altered primary beam attenuation and scatter contribution to water-equivalent material beyond high-density medium.

Discussions

Dose calculations for EBRT present challenges especially when photon beam travels through tissues with different densities such as lung, soft tissue, and bony anatomy. The accurate modeling of primary beam attenuation and lateral scatter due to presence of different media heterogeneities along the beam path is essential to prevent from dose overestimation or underestimation.

The results from phantom A indicated that PBC and

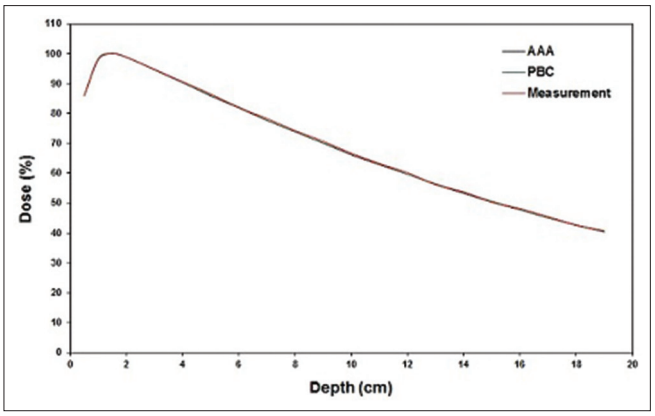

Figure 2: Central axis percent depth dose comparisons in homogeneous phantom A (solid water material) for 6 MV photon beam of field size 10 × 10 cm². Calculated and measured doses normalized to dose at depth 1.5 cm

AAA could predict the doses in good agreement with the measurements in homogenous medium where heterogeneity correction is not necessary. However, results from phantom B showed the limited accuracy of PBC and AAA in heterogeneous media and similar observations were reported by other authors.[3,8,9] Moreover, PBC and AAA have different approach of beam modeling to account the heterogeneities, and brief descriptions of both algorithms are presented below. For complete understanding on PBC and AAA, readers are advised to refer to papers authored by Carrasco *et al.*[7] and Van Esch *et al.*[8]

The PBC involves the calculation of dose distribution in infinitesimally narrow pencil beams (directed along a ray line from the beam source),[10] and dose deposition kernels or pencil kernels are derived from measured water data.[11,12] The corrections to each pencil beam are obtained by a correction factor to account for differences in attenuation.[13,14] The heterogeneity correction (modified Batho method) in PBC algorithm takes the position of the inhomogeneity with respect to the point of calculation into account.[13] However, the dose from the adjacent pencil beams is not considered in each calculation, which can lead to errors in determination of dose in tissues that are within areas of large inhomogeneity. The effect is a heterogeneity correction only in the beam path direction, but not in lateral direction.[3,13,14] The beams in AAA include separately modeled contributions from different photon sources.[3,15] The total energy deposited by each beam is obtained by the convolution of the separately modeled contributions of different photon sources and final dose is calculated by the superposition of the contributions from the beams.[3] The tissue heterogeneity in AAA is handled by radiologic scaling of primary photons and photon scatter kernel scaling in lateral directions according to local electron density.[15]

Although we were unable to make direct comparisons of our findings against previous studies on AAA and PBC due to variability in experimental set ups and difference in phantom geometries, it is relevant to mention the work of Gray *et al.*[12] who investigated the accuracy of AAA

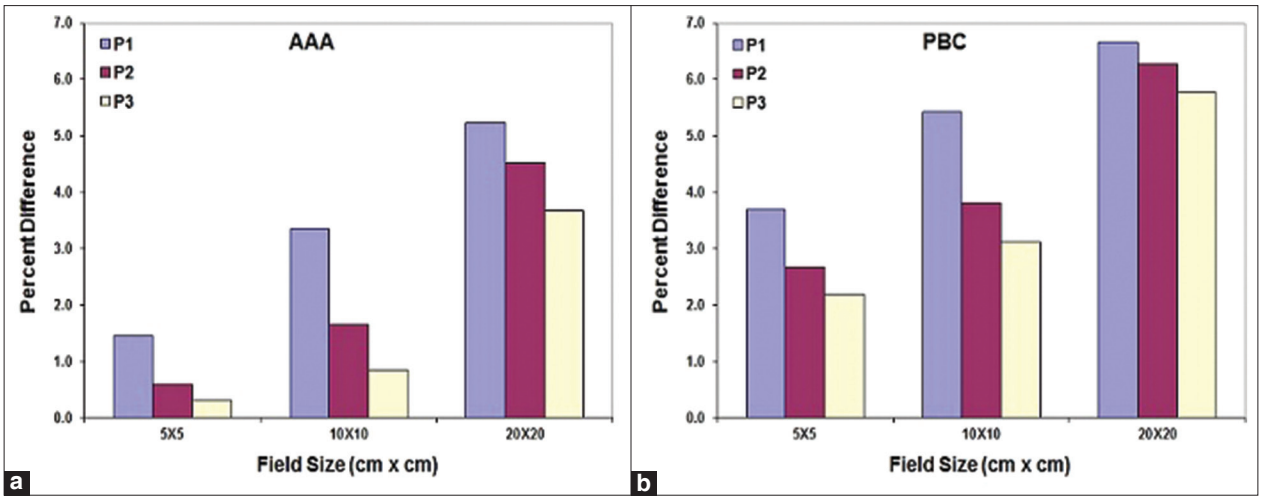

Figure 3: Comparisons between calculated (anisotropic analytical algorithm on the left and pencil beam convolution on the right) and measured percent depth doses at P1, P2, and P3 for 6 MV photon beam of field sizes 5 × 5, 10 × 10, and 20 × 20 cm². P1, P2, and P3 are points of interest as shown in Figure 1

and PBC in heterogeneous media. Gray *et al.*[12] reported that results from AAA were better than those calculated by the PBC but dose overestimation greater than 2.5% could still result when using AAA to calculate the dose beyond a large air gap. Robinson *et al.*[3] investigated the dose on the central beam axis at a vertical depth of 3 cm below the proximal surface of the heterogeneity layer of 2-10 cm air gap. Robinson reported that the AAA algorithm tends to overestimate dose beyond low density heterogeneities. This overestimation is shown to be, on average, 3% at distances less than 10 cm and up to 7% at distances greater than 10 cm. Van Esch *et al.*[8] confirmed these results as his group investigated the depth dose within a phantom consisting of 5 cm solid water, 15 cm cork, then 10 cm solid water for a variety of field sizes 3×3^2 cm to 20×20 cm^2. Their results showed that the AAA overestimated the dose by up to 7% beyond the cork slab.

The error in the AAA and PBC doses calculated beyond bony material may also occur in other clinical situations such as when the treatment beam passes through low density material (e.g., polyurethane foam) in the immobilization device prior to entering the patient and then finally reaching the tumor situated next to the bone. The errors (up to 5.3% for AAA and up to 6.7% for PBC) found in this study could potentially increase as suggested by the results in studies of Robinson *et al.*[3] and Gray *et al.*[12] that dose discrepancies beyond air gaps are also dependent on the size of the air gaps. Future work involves the measurements to investigate how different thickness of Styrofoam (air-equivalent material) as well as PVC tile (bone-equivalent material) would affect the dose estimation by AAA and PBC at the selected points of interest.

Conclusions

The ability of AAA and PBC to account for heterogeneities was investigated using five-layer heterogeneous phantom that had combination of low and high density materials. The results of AAA had better agreement with the measurements at selected depths in this study. The dose overestimation by AAA (up to 5.3%) and by PBC (up to 6.7%) was found to be higher nearby the high-density heterogeneity interface, and the dose discrepancies were more pronounced for larger field sizes. The finding of this study suggests that the AAA is more accurate than PBC for dose calculations in treating the target seated beyond high-density heterogeneity interface at deeper depths.

Acknowledgment

The author would like to thank Kevin Rogers at Arizona Center for Cancer Care for his support during the course of this project.

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How to cite this article: Rana SB. Dose prediction accuracy of anisotropic analytical algorithm and pencil beam convolution algorithm beyond high density heterogeneity interface. South Asian J Cancer 2013;2:26-30.
Source of Support: Nil. **Conflict of Interest:** None declared.

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