Dosimetric Analysis of *Rhizophora*-based Phantom Material in Radiation Therapy Applications Using Monte Carlo GATE Simulation

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Abstract

Purpose: This study aims to determine the percentage depth dose (PDD) of a phantom material made from soy-lignin bonded *Rhizophora* spp. particleboard coated with a gloss finish by using Monte Carlo Geant4 Application for Tomographic Emission (GATE) simulation. **Materials and Methods:** The particleboard was fabricated using a hot pressing technique at target density of 1.0 $g \cdot cm^{-3}$ and the elemental fraction was recorded for the simulation. The PDD was simulated in the GATE simulation using the linear accelerator Elekta Synergy model for the water phantom and *Rhizophora* phantom, and the results were compared with the experimental PDD performed by several studies. Beam flatness and beam symmetry were also measured in this study. **Results:** The simulated PDD for *Rhizophora* and water was in agreement with the experimental PDD of water with overall discrepancies of 0% to 8.7% at depth ranging from 1.0 to 15.0 cm. In the GATE simulation, all the points passed the clinical 3%/3 mm criterion in comparison with water, with the final percentage of 2.34% for *Rhizophora* phantom and 2.49% for the water phantom simulated in GATE. Both the symmetries are all within the range of an acceptable value of 2.0% according to the recommendation, with the beam symmetry of the water phantom and *Rhizophora* phantom at 0.58% and 0.28%, respectively. **Conclusions:** The findings of this study provide the necessary foundation to confidently use the phantom for radiotherapy purposes, especially in treatment planning.

Keywords: GATE, Monte Carlo, percentage depth dose, radiotherapy, *Rhizophora* phantom

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Introduction

In the planning of radiotherapy for cancer treatment, phantom material is frequently used to represent the human body. This is due to the impossibility of arranging direct radiation toward the patient before receiving radiotherapy. The market offers a variety of radiotherapy phantom materials, the most of which are constructed of acrylic and resin. In 1988, *Rhizophora* wood was discovered as a potential phantom material due to its ability to simulate human soft tissues.[1] Since then, numerous studies have been carried out to investigate the wood's potential as a phantom material, particularly for radiation and diagnostic applications.

The patient's absorbed dose varies with depth according to the percentage depth dose (PDD) in radiotherapy. It is dependent on a number of variables, including the beam's energy, depth, field size, proximity to the source, and beam collimation mechanism. PDD is crucial to determining the fluctuation of depth dose along the beam's central axis when calculating the dose that a patient will get during radiotherapy. Small ionization chambers are frequently used to detect PDD in water phantoms, where thermoluminescent dosimeters,[2] diodes, and film are occasionally used. Ionization chambers

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are chosen over the others because they are more precise and have less energy dependence.

The normalization of the dosage at depth in relation to the dose at a reference depth is what distinguishes the central axis dose distribution. The PDD above the depth of maximum dose was previously observed to decrease with depth and increase with beam energy. The most comparison of the PDD curve was made with water phantom,[3] as it closely approximates the radiation absorption and scattering properties of muscle and other soft tissues. Water is also universally available with reproducible radiation properties. However, several dosimeters are not suitable to be used in water such as ionization chamber, unless they are design to be waterproof. Previous literature also reported the use of solid water phantom to replace water for the PDD measurement.[4]

Over the past decade, Monte Carlo (MC) often actively employed in the modeling of positron emission tomography and single-photon emission computerized tomography, and with its extension, modeling of radiation therapy is made possible.[5] Extensive verification will give rise to the substantial employment of GATE as an open-source platform for simulation in radiotherapy and imaging, and with the command script design not requiring any programming language, the utilization will be made much easier for the researchers.[6-8]

In this study, the PDD was determined for water and soy-lignin bonded *Rhizophora* spp. phantom by using MC GATE simulation. The simulated PDD was then compared with the experimental PDD by various studies. The beam flatness and beam symmetry were also calculated.

Materials and Methods

Preparation of physical phantom

The soy-lignin bonded *Rhizophora* phantom prepared in particleboard slabs was fabricated in the School of Industrial Technology, Universiti Sains Malaysia. The fabrication process involves several steps, which include wood trunk collection, debarking, planing, grinding, sieving, and the measurement of the moisture content. Figure 1 illustrates several steps in the fabrication of the particleboard. The phantom was prepared at target density of 1.0 g·cm^{-3}, by using hot pressing at approximately 200°C, at the pressure of 20 MPa. The characterization of the particleboard for its suitability as phantom material in radiation study was reported in previous studies publications.[9-13] The energy-dispersive X-ray analysis was performed to obtain the elemental composition of the phantom for the simulation in GATE.

Determination of percentage depth dose

The determination of the PDD was done using the MC toolkit: GATE simulation. LINAC modeling used in this study was simulated following the LINAC Elekta Synergy in the Advanced Medical and Dental Institute, USM. Figure 2 illustrates the LINAC modeling used to simulate the determination of PDD.

Figure 1: (a) Wood truck collected from mangrove factory, (b) Debarking process of the wood trunk, (c) Wood trunk was cut into two, (d) Planning process to produce wood particles, (e) Wood particle underwent grinding process, (f) Further grinding process to produce smaller wood particles (≤500 μm)

In order to improve the quality of the studies, the AAPM research committee Task Group (TG) 268 has proposed a list of 20 – Item checklist – RECORDS – Reporting of MC radiation transport studies – to include in the reports of MC studies.[14] Table 1 reports the RECORDS checklist.

Data from the treatment head were gathered in phase space, and the command script will allow the data to be directed to the phantom for simulation. Millions of particles, including photons, electrons, and positrons, can be found in the phase space, which also carries information about their energy, position, and direction. To determine the dosage distribution in the phantom, the second section simulates the passage of particles from the measured phase space in various irradiation field configurations.

The uncertainty in dose value along the depth was computed and recorded.[15] In this work, the estimation of error in the GATE simulation was assessed by calculating the mean point-to-point dose error.[16] When 100% of the points pass the 3%/3 mm comparison, it means that all points pass the comparison. For this gamma index comparison analysis, the distance to agreement/dose difference (DTA/DD) was attained based on the comparison of the dose with dose in water. The 3 mm criterion played a significant role in the high dose gradient region, where large DDs occur.[16]

Previous literature reported the PDD investigation modeled in the EGSnrc MC code system with a default PRESTA parameter

Table 1: Records items checklist for the Monte Carlo study

Checklist item number	Item name	Description
2, 3	Code, version/release date	GATE v9.0 with geant4 v10.06.p03 and Root v6.24/0 platform Release date: February 3, 2020
4, 17	Validation	Code was being validated against experimental measurements (linear accelerator configuration for PDD measurement based on Elekta Synergy Agility LINAC (Elekta Medical Systems, Crawley, UK)
5	Timing/system configuration	CPU-based simulation: 3.9 GHz and 32 threads CPU CPU/GPU model number: Intel Xeon Gold 6242 NVIDIA Quadro P2200
8	Source description	Source of phase-space: Energy spectrum from interaction gamma radiation Electron beam with energy of 6.4 MeV was simulated (10^8 history) and the photon spectrum produced was recorded in the Root file phase space. Phase space volume is located before the multileaf collimator. The Phase-space contains photon spectrum was then simulated to get PDD with history of 2×10^9
9	Cross-sections	Cross-section data: Liver more model
10	Transport parameters	EM standard option 3 (geant4) Electron cut-off=1.0 mm Photon cut-off=0.1 mm at material phantom and default 1.0 mm for others
11	VRT and/or AEIT	Bremsstrahlung splitting with the active splitting of 100
12	Scored quantities	DoseActor
13, 18	Number of histories/ statistical uncertainty	Histories for electron beam to generate phase-space=1×10^8 while for photon phase-space is 2×10^9 Voxel size for dose image is 5 mm×5 mm×5 mm with size of the image is 30 cm×30 cm×30 cm
14	Statistical methods	Gamma index
15, 16	Postprocessing	Nil

PDD: Percentage depth dose, GPU: Graphics processing unit, CPU: Central processing unit, VRT: Variance reduction techniques, AEIT: Approximate efficiency improving techniques

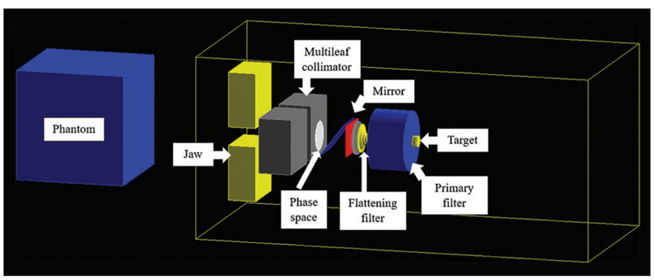

Figure 2: LINAC modeling in GATE simulation

for a 6 MV photon beam, with energy cutoff at 0.01 MeV for photon, utilizing a water phantom and an ionization chamber.[17] The quantity of PDD may be defined as the quotient, expressed as a percentage, of the absorbed dose at any depth d to the absorbed dose at a reference depth d_0, along the central axis of the beam. PDD (P) is thus defined in Equation 2.

$$P = \frac{D_d}{D_{max}} \times 100\% \quad \text{[Eq. 2]}$$

where D_d is the dose at any depth and D_{mas} is the maximum dose at reference depth.

In this study, beam profiles for water and soy-lignin *Rhizophora* spp. phantoms were produced using GATE simulation. The analysis of the beam profile using its symmetry and flatness offers data on the linear accelerator's beam quality. The photon energy homogeneity was indicated by the beam profile's flatness, and the lower the flatness value, the better the intensity uniformity across the beam. Flatness was calculated using the formula in Equation 3.

$$\text{Flatness} = 100 \times \frac{D_{max} - D_{min}}{D_{max} + D_{min}} \quad \text{[Eq. 3]}$$

For the measurement of beam flatness, the area of measurement is 80% from the central area or full width at half maximum. Beam symmetry can be calculated based on the profile in depth of maximum dose as shown in Equation 4.

$$\text{Symmetry} = 100 \times \frac{\text{area}_{left} - \text{area}_{right}}{\text{area}_{left} + \text{area}_{right}} \quad \text{[Eq. 4]}$$

For beam symmetry, it is usually specified at 10 cm and should be within ±2 and over 80% of the field.

Simulation of PDD in GATE

Figure 3 depicts an illustration of a lateral dosage profile used to construct the PDD curve from simulated data in vv 4D Slicer.[18] The graph in Figure 4 shows the PDD curve following the GATE simulation using the *Rhizophora* spp. phantom and water phantom, and a comparison was made with the experimental water phantom by a previous study. The yellow symbol depicts the PDD curve for the GATE-simulated soy-lignin bonded *Rhizophora* phantom. The simulated PDD and experimental PDD of water were in agreement overall, with differences ranging from 0% to 8.7% for depths between 1.0 and 15.0 cm. This result is a little higher than that of the earlier study that used the *Rhizophora* phantom to assess PDD at high-energy photons.[4] The buildup zone, which may be the result of forward-scattered electrons that stop at deeper depths, has the biggest percentage differences. The buildup

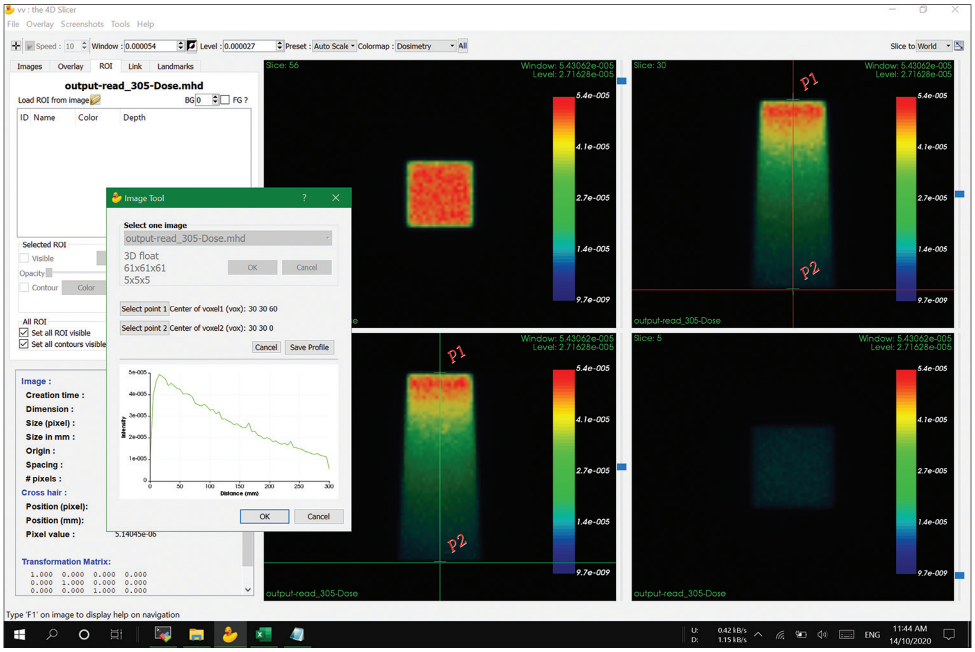

Figure 3: Example of lateral dose profile obtained from vv 4D Slicer

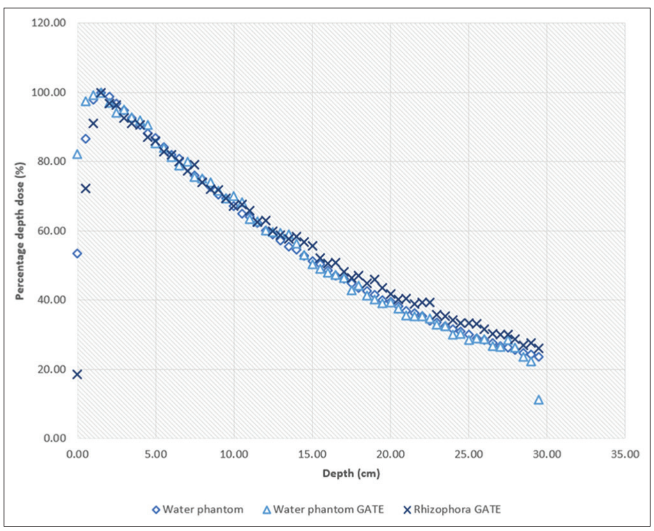

Figure 4: Percentage depth dose curve comparison for water phantom, water phantom by GATE, and *Rhizophora* spp. by GATE

region may also be caused by secondary charged particles with relatively long ranges that interact with photons inside the phantom, such as in the photoelectric effect, Compton effect, and pair production.

Table 2 demonstrates the dose value and uncertainties in dose along the depth from 0 to 15.0 cm for water and *Rhizophora*. Based on the result, the error value recorded for water in GATE is between 0.062 and 0.088, and between 0.065 and 0.091 for *Rhizophora*. All the error values along the depths are lower than 0.1. In this study, the ϵ_n was quantified to balance the point-to-point errors according to the dose deposited to allow the overall error calculated more suited in characterizing the simulation agreement with measurements.

The simulation was evaluated by gamma index by taking into account the maximum DD and the DTA requirements based on previous literature.[19] Based on the results, all the points passed the clinical 3%/3 mm criterion in comparison with dose in water, with the final percentage of 2.34% for soy-lignin bonded *Rhizophora* phantom and 2.49% for water phantom simulated in GATE. Previous literature reported that there is an inconsistent selection of passing criterion for gamma index in the assessment of intensity-modulated radiation therapy quality assurance, which may reflect the capacity and evaluation of the measurement.[20] Previous literature also demonstrated an external-beam radiotherapy with GATE, which is validated with depth-dose in water and gamma index, with more than 90% of the points are within the 3%/3 mm gamma criterion.[15] In AAPM TG-119, the parameters used were 3 mm/3% with a 90% passing percentage employed as the passing criterion,[21] with the author came into the conclusion that these parameters were empirically determined, thus requiring further extensive discussion for validation. Figure 5 illustrates the comparison of the PDD curve for water phantom, EGSnrc MC simulation, *Rhizophora* phantom, solid water phantom, soy-bonded *Rhizophora* phantom, EGSnrc simulation for *Rhizophora*, water phantom by GATE, and soy-lignin bonded *Rhizophora* by GATE.

Based on the PDD comparison, higher surface dose can be observed in most of the studies, which may be the result of energy dependence in the electron contamination of the primary beam. The photon beam collimators, which are a source of secondary electrons that pollute the beams and raise the surface dosage, may be one of the causes.[22] However, the surface dosage appears to be lower for the PDD curve that GATE simulated, which may be explained by the absence of specific parameters that could have influenced electron

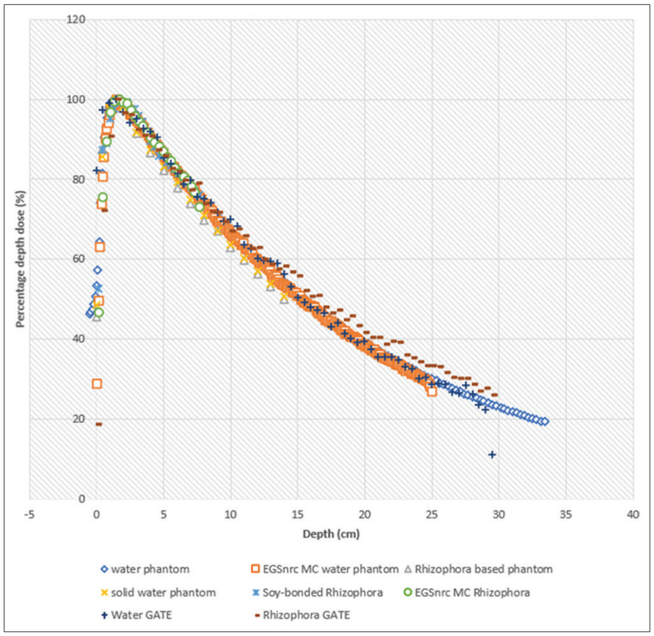

Figure 5: Comparison of percentage depth dose curve in various studies comprises water and *Rhizophora* phantom by experiment and by simulation.[17] MC: Monte Carlo

contamination during the design and simulation. This outcome is consistent with earlier research that measured PDD using MC dose computation.[23-25] The dosage calculation produced by GATE simulation may have a good statistic, but there are always uncertainties in every measurement that may result from repeated and multiple geometry updates and command file configuration.

The dose profile generated from the GATE simulation was also analyzed based on the symmetry and flatness across the beam. The dose profile was generated by indicating the beam intensity across the horizontal line, perpendicular to the direction of the beam. The resulting dose profile offers details on the beam quality and the linear accelerator's design quality. Beam profile at depth of maximum dose, $d_{max,}$ and reference depth, d_{ref} which is the depth at 95% of the given dose.

Table 3 shows the comparison of beam flatness for water phantom, water phantom simulated by GATE, and soy-lignin bonded *Rhizophora* phantom simulated by GATE. The beam profile for the water phantom and soy-lignin bonded *Rhizophora* phantom simulated in GATE at d_{max} and d_{ref} were presented in Figures 6 and 7. The value was recorded as percentage dose, with the photon energy deposited at 100% PDD and 95% reference dose, and the calculated profile was satisfactory based on the symmetry and the flatness. In this study, the beam flatness for both water phantom and soy-lignin bonded *Rhizophora* phantom were 2.70 and 3.18 at $d_{max,}$ which fall within the acceptable range. Based on the recommendations by AAPM Report 32, the useful limit for flatness is ±3% across the beam profile, while the symmetry between the opposite site should not be more than 2%.[26-28] The symmetry and flatness that fell within these limits indicate that the model is reasonably accurate in terms of beam energy and interaction quality. Based on the result, both the symmetries

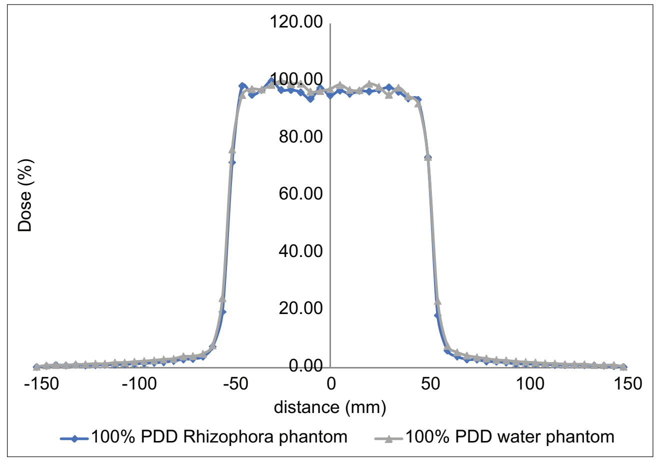

Figure 6: Beam profile of water phantom and soy-lignin bonded *Rhizophora* spp. phantom simulated in Monte Carlo GATE at d_{max}. PDD: Percentage depth dose

Table 2: Dose and uncertainty along the depth in GATE simulation for water and *Rhizophora*

Depth (mm)	Depth dose % (uncertainty)	
	Water	*Rhizophora*
0	82.11 (0.06)	18.62 (0.07)
5	97.34 (0.06)	72.26 (0.07)
10	99.13 (0.06)	90.95 (0.07)
15	100.00 (0.06)	100.00 (0.07)
20	96.98 (0.06)	96.66 (0.07)
25	94.26 (0.06)	96.27 (0.07)
30	95.00 (0.06)	92.52 (0.07)
35	92.80 (0.07)	91.00 (0.07)
40	91.96 (0.06)	90.64 (0.07)
45	90.51 (0.06)	87.20 (0.07)
50	85.35 (0.06)	85.97 (0.07)
55	83.91 (0.06)	82.75 (0.07)
60	81.34 (0.07)	82.05 (0.07)
65	78.77 (0.07)	79.90 (0.07)
70	79.97 (0.07)	77.32 (0.07)
75	75.54 (0.07)	79.17 (0.07)
80	75.18 (0.07)	74.00 (0.07)
85	74.08 (0.07)	71.97 (0.07)
90	71.72 (0.07)	71.75 (0.07)
95	69.52 (0.07)	69.33 (0.07)
100	69.92 (0.07)	67.22 (0.07)
105	68.31 (0.07)	67.58 (0.07)
110	63.48 (0.07)	65.76 (0.07)
115	62.83 (0.07)	62.52 (0.07)
120	60.05 (0.07)	63.00 (0.07)
125	59.71 (0.07)	59.91 (0.07)
130	59.43 (0.07)	58.82 (0.07)
135	59.00 (0.07)	57.57 (0.07)
140	56.38 (0.07)	58.17 (0.08)
145	52.99 (0.07)	56.93 (0.08)
150	50.39 (0.09)	55.71 (0.09)

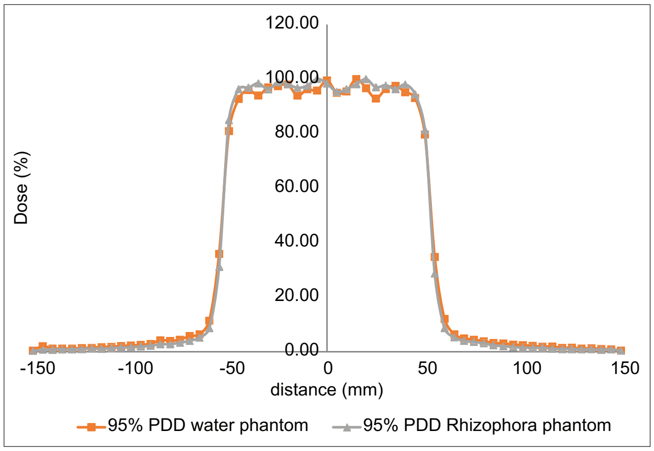

Figure 7: Beam profile of water phantom and soy-lignin bonded *Rhizophora* spp. phantom simulated in Monte Carlo GATE at $d_{ref.}$ PDD: Percentage depth dose

Table 3: The measured beam flatness of water and *Rhizophora* phantom at 6 MV photon

Depth	Beam flatness (%)	
	Water phantom GATE	*Rhizophora* GATE
d_{max}	2.70	3.18
$d_{ref\ at\ 95\%\ dose}$	3.72	2.41

are all within the range of acceptable value of 2% according to the recommendation, with the beam symmetry of the water phantom and soy-lignin bonded *Rhizophora* phantom at 0.58% and 0.28%, respectively.

This study has presented a GATE-based simulation tool that has been developed. It has been shown that this tool is capable of simulating the dosimetric characteristics of a linear accelerator with a 6 MV Elekta Synergy Platform accurately. The main accelerator head parts have been carefully modeled in accordance with the manufacturer's specifications with GATE's flexibility. The findings from the GATE simulation for the soy-lignin bonded *Rhizophora* phantom in terms of percentage depth dosage and lateral beam profiles exhibit excellent agreement with the experimental data obtained with incident mean electron energies of 6.4 MeV, modeling at 6 MV photon energy.

Conclusions

The PDD for water and soy-lignin bonded *Rhizophora* phantom was in agreement with the experimental PDD of water with overall discrepancies of 0%–8.7% at depth ranging to 15.0 cm. In the GATE simulation, all the points passed the clinical 3%/3 mm criterion with the final percentage of 2.34% for the *Rhizophora* phantom and 2.49% for the water phantom simulated in GATE. Both the symmetries are all within the range of an acceptable value of 2% according to the recommendation, with the beam symmetry of the water phantom and *Rhizophora* phantom at 0.58% and 0.28%, respectively. This work illustrates how MC GATE, particularly in the PDD assessment, can be exploited for radiation therapy applications. The construction of GEANT4 simulations is greatly facilitated by the straightforward macro file format. To distinguish the final result, additional validation can be carried out using various energies and other linear accelerator specifications. The results also provide the solid groundwork needed to reliably employ the phantom in radiation, particularly in treatment planning.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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