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Tannin-Bonded *Rhizophora* spp. Particleboards as Water Equivalent Phantom Material for High Energy Photons and Electrons

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A B S T R A C T

Phantom materials are important tools for quality control and dosimetry works in medical physics. The tannin-bonded *Rhizophora* spp. particleboards in were fabricated as phantom and the dosimetric properties at high energy photons and electrons were evaluated. The particleboards were fabricated at dimensions of 30 x 30 x 1 cm^3 and target density of 1.0 g/cm^3 based on the commonly used solid water phantoms in radiotherapy. The effective atomic number of the particleboard was determined based on the elemental compositions measured using energy dispersive x-ray analysis (EDXA). The mass attenuation coefficients at high energy photon were measured at 16.59-25.26 keV photons and ^{60}Co and ^{137}Cs gamma energies. The percentage depth dose and beam parameters of the particleboards were measured at 6 MV photons and 6 MeV electrons using Gafchromic EBT2 film and treatment planning system (TPS) software. The results showed that the effective atomic number and electron density of the particleboards were close to the value of water. The mass attenuation coefficient at high energy photons were close to the XCOM value of water. The percentage depth dose at high energy photons and electrons showed an agreement to the value in water and solid water phantom within 10% at all measured depths. The overall results indicated the suitability of tannin-bonded *Rhizophora* spp. as phantom material for high energy photons and electrons.

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INTRODUCTION

Phantoms are the materials that simulate the absorption and scattering characteristics of human soft tissues towards ionizing radiations [1]. Phantoms become important tools for quality assurance, calibration and dosimetric studies involving high energy photons and electrons to ensure the precision of beam delivery in a radiotherapy treatment. An ideal phantom material shall have density and attenuation properties similar to the human soft tissues. The commonly available dosimetric protocols had suggested water as phantom material for high energy photons and electrons due to its near density to human soft tissue. The use of water however is not always convenience due to its liquidity and compatibility of most radiation dosimeters to be used in water. Several solid-state phantoms such as acrylic, Perspex® and polystyrene were developed to substitute water but still failed to accurately simulate the attenuation of water at various range of photons.

Rhizophora spp. had been identified as potential phantom material due to its mass density and attenuation properties near to the value of water [2,3]. A dosimetric study on high energy photons and electrons also showed good agreement of depth dose in raw *Rhizophora* spp. wood to water [4]. The use of raw *Rhizophora* spp. wood however came into several limitations including limited size for full standard phantom size, and tendency to crack and bend over period of time. Shakhreet et al., [5] had studied the fabrication of *Rhizophora* spp. particleboards that enables the fabrication at various size and shapes. The results showed that the fabrication of *Rhizophora* spp. particleboards did not significantly change its attenuation properties towards photons. The fabrication of *Rhizophora* spp. particleboards however had reduced the physical strength of *Rhizophora* spp. phantoms [6,5]. The use of synthetic-based adhesives such as urea-formaldehyde (UF) commonly used in industry had

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significantly lowered the density and mass attenuation coefficients of *Rhizophora* spp. [7,8]. The biological-based adhesives on the other hand were found to increase the physical properties of *Rhizophora* spp. particleboards and at the same time retaining its attenuation properties at various clinical applications [9,10,11].

Tannin had been widely used as adhesives for particleboard and wood panel industries [12,13]. Previous study had indicated the potential use of *Rhizophora* spp. tannin extracted from the bark as potential adhesive material for *Rhziophora* spp. phantom material at mammographic X-ray energy ranges [14]. The present study focused on the use of commercialized tannin in form of tannic acid powder as bio-adhesive material for *Rhizophora* spp. particleboards in application of high energy photons and electrons.

The commercialized tannin used in the present study having the molecular formula of $C_{76}H_{52}O_{56}$ which is comparable to the composition of soft tissues with a molecular weight of 1701.2 g/mol. A calculation of effective atomic number showed that tannic acid has an effective electron density of 6.937, which is near to the value of water (7.42) [15].

MATERIAL AND METHODS

Fabrication of Particleboard Phantoms

A set of thirty *Rhizophora* spp. particleboards were fabricated at target density of 1.0 g/cm^3 and dimensions of 30 cm x 30 cm x 1 cm according to the commonly used solid water phantoms. An amount of 10% tannin were added during the fabrication of the particleboards based on the measured dried mass of *Rhizophora* spp. wood particles required to achieve the target density. The moisture content of the wood particle was kept lower than 7% to prevent water accumulation during the hot pressing that would cause blistering and swelling to the particleboard surface. The particleboards were fabricated by the method of hot pressing with temperature and pressure of 200ºC and 20 MPa respectively based on the study by Marashdeh et al., [6]. The average density of the particleboards were measured using gravimetric method based on the external dimensions given by the equation

$$\rho = \frac{length \times width \times thickness}{mass} \tag{1}$$

Elemental Compositions and Effective Atomic Number

The percentage of elemental compositions of the tannin-bonded *Rhizophora* spp. particleboards was measured using energy dispersive X-ray analysis (EDXA). The effective atomic number Z_{eff} of the particleboard was calculated based on the study by Duvauchelle et al., [16] using the equation

$$Z_{eff} = \left[\sum_{i=1}^{n} (\alpha_i \, z_i^m)\right]^{\left(\frac{1}{m}\right)} \tag{2}$$

with α_i and z_i are the electron fraction and the atomic number of the i^{th} element in the sample, and m is the experimental coefficient for biological materials and water, having a value of 3.4. The electron fraction of the i^{th} element was calculated using the equation

$$\alpha_i = \frac{wi\left(\frac{z_i}{A_i}\right)}{\Sigma w_i\left(\frac{z_i}{A_i}\right)} \tag{3}$$

with w_i and A_i are the fractional weight and atomic mass of the i^{th} element respectively. The calculated value of Z_{eff} of the *Rhizophora* spp. particleboards were compared to the value of water [15].

Determination of CT Number

The CT number of a medium is proportional by the its attenuation property as shown by the equation

$$CT\ number = 1000\ \frac{\mu - \mu w}{\mu w} \tag{4}$$

With μ and μ_w is the linear attenuation coefficient of the medium and water respectively. The CT number of tannin-bonded *Rhizophora* spp. was measured to determine its water and tissue equivalent property. The particleboard was sawn circularly with diameter of 3 cm made compatible for electron density phantom model CIRS 062M. The CT image of the particleboards was obtained at 120 kVp CT X-ray energy with 250 mAs exposure factors using abdominal scanning protocol. The CT number of the particleboard was measured from the CT image and compared to the value of water and other soft tissues including adipose, liver, muscle and breast density plug phantoms of the electron density phantom. The density profile was plotted to determine the uniformity of density in the tannin-bonded *Rhizophora* spp.

Measurement od Mass Attenuation Coefficients

The mass attenuation coefficients of tannin-bonded *Rhizophora* spp. particleboards at low energy photons were measured using an XRF configuration as shown in Figure 1 (a). An annular ^{241}Am source with peak gamma energy of 59.59 keV was used in the XRF configuration in conjunction with niobium, molybdenum, palladium and tin plates that provided kα1 photons of 16.59, 17.46, 21.21 and 25.26 keV respectively. The transmitted photons were collected by a low energy germanium detector (LEGe) connected to a single channel analyzer (SCA). The mass attenuation coefficients at high energy photons were measured using Ludlum configuration in conjunction with ^{137}Cs and ^{60}Co sealed sources that provided gamma energies of 0.662 and 1.2 MeV respectively. The transmitted photons in XRF and Ludlum configurations were measured as count per minute (CPM). The linear attenuation coefficients of the particleboards were determined based on the transmitted photons according to the Beer-Lambert law given by the equation

$$I = I_{\circ}\, e^{-\mu x} \tag{5}$$

with $I_{\circ}$ is the initial intensity of photons, μ is the linear attenuation coefficient of the sample, and x is the thickness of the particleboard samples. The value of the linear attenuation coefficient was calculated using the equation

$$\mu = \frac{1}{\chi}\ln\left(\frac{I_{\circ}}{I}\right) \tag{6}$$

The value of the mass attenuation coefficient is obtained by dividing the value of the linear attenuation coefficient by the density of the particleboard.

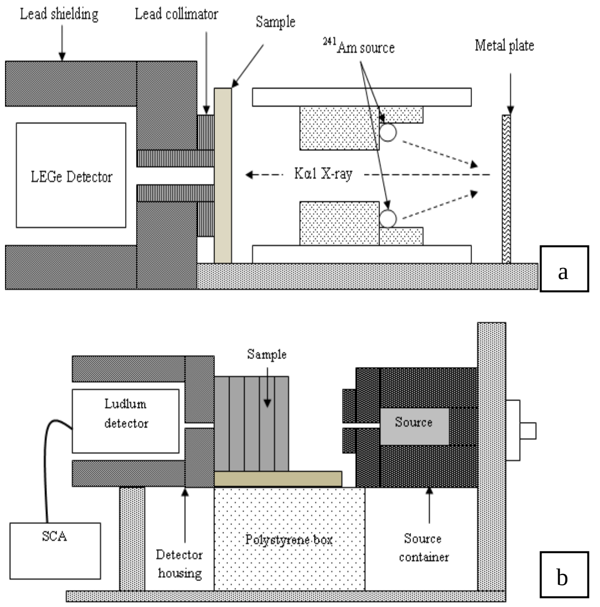

Figure 1. The experimental set up of (a) X-ray fluorescence (XRF) and (b) Ludlum configuration used for determination of mass attenuation coefficients

Measurement of Percentage Depth Dose at High Energy Photons and Electrons

The percentage depth doses (PDD) of tannin-bonded *Rhizophora* spp. particleboards were measured using a clinical linear accelerator. The depth dose in the particleboards were measured at 6 MV photons and 6 MeV electrons using Gafchromic EBT2 radiochromic film dosimeter (EBT2) and treatment planning system (TPS) computer. The depth dose using EBT2 film was measured by placing the film at the midplane of the particleboards. Irradiations were made parallel to the beam with 10 x 10 cm field size and 100 cGy dose based on IAEA TRS398:2000 codes of practice as shown in Figure 2(a). The depth dose using TPS were done by scanning the particleboards using a CT scan as an input to the TPS system. The beams were simulated according to IAEA TRS398:2000 (10 x 10 cm field size and 100 cGy dose) as shown in Figure 2(b). The PDD values of the particleboards were based on the ratio between the dose at depth, D to the maximum dose, D_{max} given by the equation

$$PDD = \frac{D}{D_{max}} \times 100\% \tag{7}$$

The PDD curve of the particleboards were plotted and compared to water and solid water phantoms as standard phantom materials used in radiotherapy.

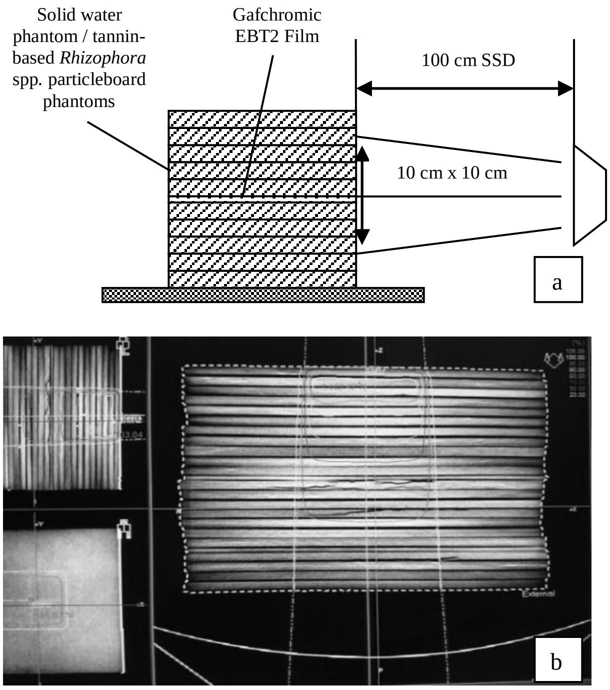

Figure 2. The measurements of PDD using (a) EBT2 film dosimeter and (b) treatment planning system (TPS)

RESULTS AND DISCUSSION

Analysis of Physical Properties

The average density of tannin-based *Rhizophora* spp. particleboard phantoms measured using gravimetric method is presented in Table 1. The results showed that all particleboards had achieved density near to the value of water (1.0 g/cm^3). The results were in good agreement to the previous study by Bradley et al., [2] who measured the average density of raw *Rhizophora* spp. wood. The densities of the particleboards also showed good uniformity shown by the standard deviation value.

The percentage of elemental compositions of tannin-based *Rhizophora* spp. particleboards is presented in Table 2. The results showed that the elemental compositions of tannin-bonded *Rhizophora* spp, showed high percentage of carbon and oxygen which is similar to the elemental compositions of human soft tissue. The calculation of Z_{eff} also showed close value to that in water indicating its water equivalent property. The results were in good agreement to the previous studies by Bradley et al.,[2] who measured the Z_{eff} of raw *Rhizophora* spp. wood. The results were also in good agreement to the previous studies on the fabrication of particleboards as phantoms [9,10,14,11,15].

The average CT number of tannin-bonded *Rhizophora* spp. particleboards at 120 kVp CT X-ray energy is presented in Table 3. A comparison of CT number to the other tissue equivalent density plug phantoms showed close value of CT number to water. The results had indicated the water equivalent property of tannin-bonded *Rhizophora* spp. particleboards based on the CT number [17].

TABLE 1. The average density of tannin-bonded *Rhizophora* spp. particleboards.

Density, ρ (g/cm³)			Standard Deviation
Max	Min	Average	
1.021	0.985	1.001	0.014

TABLE 2. The percentage of elemental compositions and effective atomic number of *Rhizophora* spp. particleboards

Sample	Elemental composition (%)					Z_{eff}
	Hydrogen	Carbon	Oxygen	Nitrogen	Fluorin	
Tannin-bonded *Rhizophora spp.*[a]	-	51.25	43.11	-	5.64	7.22
Binderless *Rhizophora spp*.[b]	5.41	48.32	54.4	0.03		-
Rhizophora spp. raw wood[c]	3.78	40.16	47.9	3.78		-
Water[d]	11.11	-	88.89	-	-	7.42
Tannin[a]	2.79	49.03	48.18			6.95

[a]Current study, [b]Marashdeh et al (2012), [c]Bradley et al (1991), [d]AAPM-21 (1983)

TABLE 3. The average CT numbers of tannin-bonded *Rhizophora* spp. Particleboards and other tissue equivalent phantoms

Density plug phantom	Density (g/cm³)	Mean CT Number (HU)			Standard Deviation
		Average	Max	Min	
Adipose Tissue	0.970	-78.75	60	-207	32.54
Breast (50/50)	0.990	-52.09	76	-164	38.05
Water	1.004	-11.60	119	-133	37.19
Muscle	1.060	27.36	164	-93	29.69
Tannin-bonded *Rhizophora* spp.	1.001	-18.43	94.53	-118.47	39.78

Analysis of Mass Attenuation Coefficients

The mass attenuation coefficients of tannin-bonded *Rhizophora* spp. particleboards at low and high energy photons are presented in Table 4. The mass attenuation coefficients of the particleboards were found to be close to the calculated value of water using XCOM [18]. A comparison to the raw *Rhizophora* spp. wood showed that the fabrication of particleboards had improved the attenuation properties of *Rhizophora* spp.

TABLE 4. The linear and mass attenuation coefficients of tannin-bonded *Rhizophora* spp. particleboards at low and high energy photons

Energy		Tannin-bonded *Rhizophora* spp.	Raw *Rhizophora* spp. wood	Water (XCOM)
Nb	μ	1.142	1.136	1.193
(16.59 keV)	μ/ρ	1.072	1.135	1.193
Mo	μ	1.072	0.921	1.095
(17.46 keV)	μ/ρ	1.011	0.921	1.095
Pd	μ	0.731	0.659	0.755
(21.21 keV)	μ/ρ	0.718	0.659	0.755
Sn	μ	0.486	0.440	0.506
(25.26 keV)	μ/ρ	0.478	0.440	0.506
^{137}Cs	μ	0.079	0.067	0.086
(0.662 MeV)	μ/ρ	0.079	0.067	0.086
^{60}Co	μ	0.056	0.053	0.059
(1.2 MeV)	μ/ρ	0.054	0.054	0.059

The mass attenuation coefficients of a material are an important parameter to determine the attenuation properties and the suitability of a material as phantoms. A phantom material shall have similar value of mass attenuation coefficients to the standard phantom material (water and soft tissues). The mass attenuation coefficients of tannin-bonded *Rhizophora* spp. particleboards were found to be close to the values of water calculated using XCOM at low and high energy photons. The results was in good agreement to the previous studies on the attenuation properties of fabricated *Rhizophora* spp. particleboards as phantoms [9,10,6,19,14,11]. The results had also indicated the suitability of the experimental set up XRF and Ludlum configurations as methods for the measurements of mass attenuation coefficients.

Analysis of Percentage Depth Dose in High Energy Photons and Electrons

The PDD of tannin-bonded *Rhizophora* spp. particleboards at 6 MV photons and 6 MeV electrons using EBT2 film dosimeter and TPS computer is shown in Figure 3 and 4 respectively. The PDD of tannin-bonded *Rhizophora* spp. were in good agreement to solid water and water phantoms at 6 MV photons and 6 MeV electrons within maximum percentage of discrepancies of 10% as shown in Figure 3(a) and 3(b) respectively when measured using EBT2 film dosimeter. The PDD measurement using TPS computer showed that the PDD of tannin-bonded *Rhizophora* spp. were in good agreement to solid water phantoms within 6% at 6 MV photons and 6 MeV electrons as shown in Figure 4(a) and 4(b) respectively. A comparison to water (ionization chamber) however showed significant different of PDD at depth beyond d_{max} for 6 MeV electrons.

The PDD had been commonly used to determine the attenuation and dosimetric properties of a medium in clinical photons and electrons. The dose at depth as well as the maximum dose received resulted from the delivery of photons and electrons shall be evaluated from the PDD curve. The PDD also had become the basis for the output calibration and quality assurance for high energy photons and electrons. Film dosimeters including the EBT2 on the other hands had been extensively used for dosimetry works in radiotherapy due to its good spatial resolution and wide range of dose range especially in a mixed-field radiation beam such as the intensity modulated radiation therapy (IMRT) [20,21].The TPS software had been commonly used in treatment planning in radiotherapy that includes the clinical set up of the radiation beams and the simulations of dose based on the CT images and planned radiation beams. The PDD of tannin-bonded *Rhizophora* spp. were found to be in good agreement to water and solid water commonly used as standard phantoms in radiotherapy in both 6 MV photons and 6 MeV electrons. A comparison between the PDD curves in EBT2 film and TPS showed good agreement between the two methods. The surface doses of the particleboards were found to be lower than that in water and solid water. The PDD of the particleboards showed an excellent agreement within 4% to water and solid water at the build-up regions in both photons and electrons. The percentage of discrepancies however increased at depths beyond the d_{max} within 10% to water and solid water. The overall results were in good agreement to the previous work on the PDD of raw *Rhizophora* spp. wood in 6 MV photons and 5 MeV electrons [4].

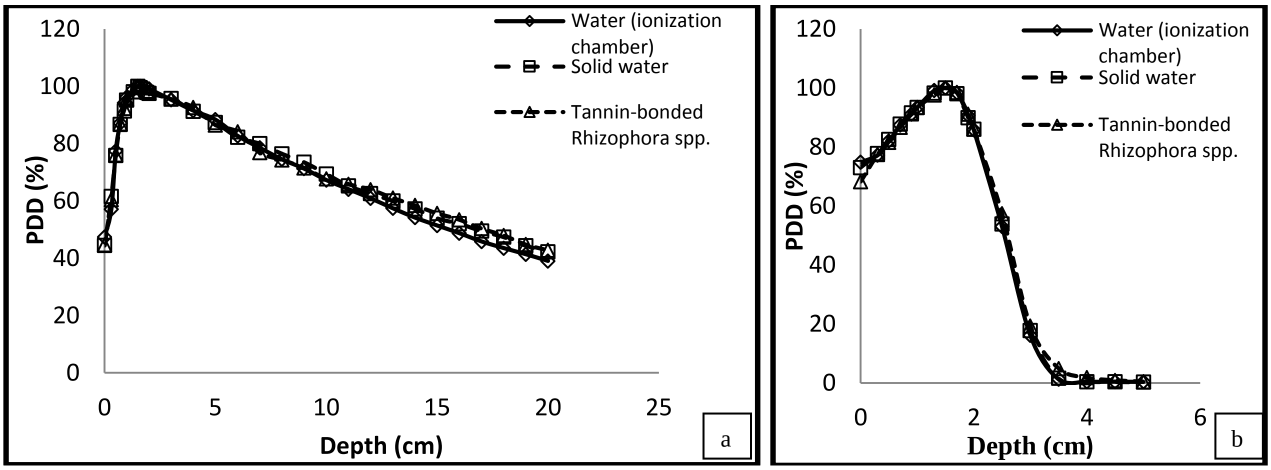

Figure 3. The PDD curve of (a) 6 MV photons and (b) 6 MeV electrons measured using EBT2 film.

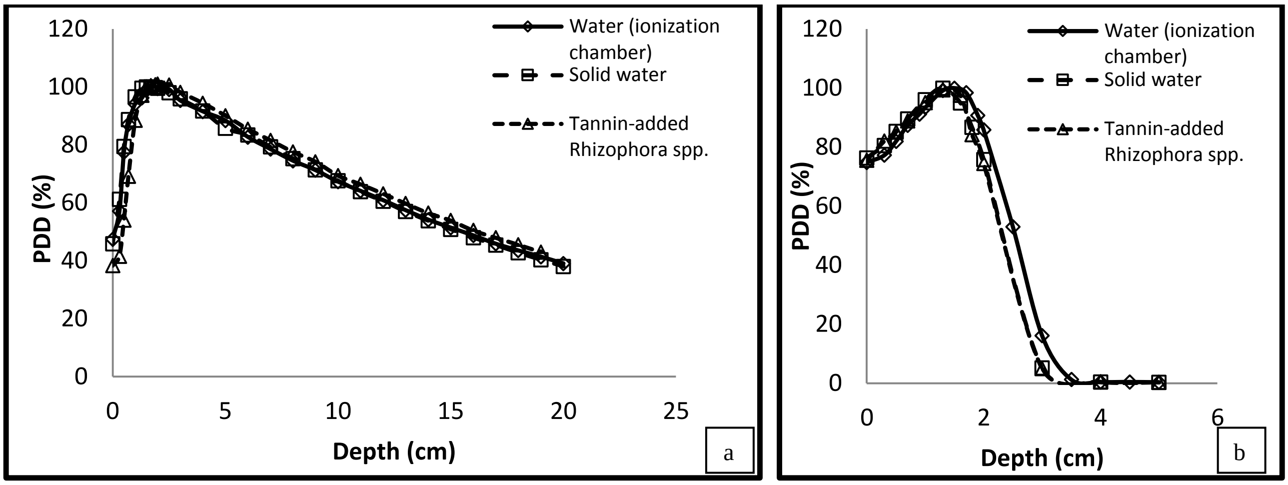

Figure 4. The PDD curve of (a) 6 MV photons and (b) 6 MeV electrons measured using treatment planning system (TPS).

CONCLUSION

The fabricated tannin-bonded *Rhizophora* spp. particleboards had achieved the effective atomic number and CT number close to the value of water indicating its water equivalent properties to be used as phantoms. The measurement of mass attenuation coefficients also showed that the value of tannin-bonded *Rhizophora* spp. were in good agreement to the calculated value of water using XCOM. The measurements of percentage depth dose at high energy photons and electrons had shown good agreement to water and solid water that are commonly used as phantoms in radiotherapy. A comparison of percentage depth dose curve also showed a good consistency between the EBT2 film and TPS software. The overall results had indicated the suitability of tannin-bonded Rhizophora spp. particleboards to be used as phantoms for dosimetry works involving high energy photons and electrons.

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Persian Abstract

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چکیده

مواد فانتوم ابزار مهمی برای کنترل کیفیت و کارکرد دوزیمتری در فیزیک پزشکی است. Rhizophora spp. تانن پیوند خورده تخته خرده چوب در فانتوم ساخته شد و خواص دزیمتری در فوتون های انرژی بالا و الکترون ها مورد بررسی قرار گرفت. تخته خرده چوب در ابعاد ۳۰ × ۳۰ × ۱ سانتی متر و تراکم هدف ۱,۰ g / cm3 بر اساس فانتوم آب معمولی استفاده شده در پرتودرمانی ساخته شد. تعداد اتمی موثر تخته خرده چوب بر اساس ترکیبات عنصری اندازه گیری شده با استفاده از تحلیل انرژی اشعه ایکس (EDXA) اندازه گیری شد. ضرایب انقباض جرمی در فوتون با انرژی بالا در فوتون های ۱۶,۵۹-۲۵,۲۶ کیلووات و انرژی های گاما ۶۰ Cu و Cs۱۳۷ اندازه گیری شد. درصد درصد عمق و پارامترهای پرتو تخته خرده چوب در فوتون های ۶ مگاوات و الکترون های ۶ مگاوات با استفاده از نرم افزار Gffchromic EBT2 و سیستم برنامه ریزی درمان (TPS) اندازه گیری شد. نتایج نشان داد که تعداد اتم موثر و چگالی الکترونی تخته خرده چوب به مقدار آب بستگی دارد. ضریب تضعیف جرمی در فوتون های انرژی بالا نزدیک به مقدار XCOM آب بود. درصد درصد عمق در فوتون های با انرژی بالا و الکترون ها در مقدار ۱۰ درصد در تمام عمق های اندازه گیری شده با مقدار فانتوم آب و آب جامد موافق است. نتایج کلی نشان داد که مناسب بودن ریزوفورا با تانن پیوند خورده است.