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Comparisons of various water-equivalent materials with water phantom using the Geant4/GATE simulation program

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► ***Original article***

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ABSTRACT

Background: The aim of this study was to compare the dosimetric properties of various water- equivalent phantom materials, such as solid water WT1 (WT1), solid water RMI457 (RMI457), plastic water, virtual water, polymethyl methacrylate (PMMA), polystyrene and A150, with water phantom. ***Materials and Methods***: Percentage depth dose values were obtained with IBA Blue Phantom[2] and solid water phantom (RW3) used in clinical radiotherapy. The measurements were carried out at 6 and 18 MV photon energies with a field size of 10 x 10 cm^2 and source-skin distance (SSD) at 100 cm. Simulations for the commercial solid phantoms were performed under these same conditions using Geant4 Application for Tomographic Emission (Geant4/GATE) simulation code. ***Results***: PMMA (3.66±1.43) % and A150 (2.40±2.20)% phantom materials were determined to have a low rate of water equivalence at 6 MV photon energy while WT1 (-2.80±2.17)% and plastic water (-2.04±2.13)% phantom materials showed a low rate of water equivalence at 18 MV photon energy. Solid water WT1 (0.13±1.11)% and RMI457 (-0.29±0.91)% phantom materials were seen to be good water-equivalent materials at 6 MV photon energy, while PMMA (-0.08±1.39)% and A150 (-1.08±1.53)% were the closest equivalent materials to water at 18 MV photon energy. ***Conclusion***: All the materials examined in this study were found to be suitable for the daily dosimetric measurements in clinical applications. The most appropriate choice would seem to be to use water phantom for the dosimetric measurements in radiotherapy clinics depending on the possibilities and time.

INTRODUCTION

Radiotherapy is a treatment method where high-dose radiation is used to kill cancerous cells and shrink the tumor in the human body. The main purpose of radiotherapy applications is to apply the highest dose to tumorous tissue while protecting the surrounding healthy tissue as much as possible (1, 2). The importance of determining the radiation dose given to the patient and the quality assurance of the dose in the planning and administration of the treatment is of increasing importance (3, 4).

With recent technological developments, software and algorithm applications have come to the fore in confirming the accuracy of research and examinations related to radiation studies(5). To be able to reveal the effects of radiation on the human body more clearly, researchers have studied phantom materials with an effective atomic number, attenuation coefficient and scattering properties equivalent to water or tissue. These phantom materials are generally accepted as human tissue equivalent material in terms of size, density and the interaction of radiation with matter (6). International dose protocols such as the American Association of Physicists in Medicine (AAPM) TG-51 and International Atomic Energy Agency (IAEA) TRS-398 recommend using water phantom for dose measurements (1, 7). Water is frequently used in radiotherapy for the dosimetric measurements because of its availability, reusability and density close to that of soft tissue (8). Water phantom is used as a reference phantom material since the majority of the human body consists of water, and it is easily definable (9-11). As water phantom has a long installation duration and is impractical to use, solid water phantom is preferred in daily or weekly routine quality assurance measurements in radiotherapy clinics (4, 12-14). The installation of these phantoms is fast and measurements can be repeated. In this regard, it has an important role in confirming the accuracy of the given dose. There are various water-equivalent commercial solid phantom materials. The most important feature of these phantoms is that they can effectively simulate the dose response of the water at different energies. In addition to the dosimetric properties of various phantom materials, research is also ongoing into the production of new phantoms from different materials (15-22). The main requirements of phantom design

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include mechanical resistance and flexibility. Many plastic and polymer materials are used for dosimetry in radiotherapy units. These materials are used as tissue equivalents in the field of medical physics and dosimetry applications due to their physical and chemical properties [23, 24]. Commonly used materials are PMMA, polystyrene, epoxy resin, and virtual water, There are a few studies in the literature comparing the water equivalence of these materials [18-21]. However, the tissue-equivalent solid phantoms used still do not exactly comply with the radiological properties and attenuation coefficient parameters of water at both low and high energies [25].

The aim of this study was to simulate the percentage depth dose (PDD) values of various water -equivalent phantom materials such as WT1, RMI457, plastic water, virtual water, PMMA, polystyrene and A150 using GEANT4/GATE. The Phantom materials that can be used as dosimetry in radiotherapy clinics were examined; the $TPR_{20/10}$ results of these materials were obtained. The usability of phantom materials in calibration processes was evaluated. Additionally, a reference study was presented for quality control processes.

MATERIALS AND METHODS

The experiments were performed using a Linear Accelerator (Elekta Synergy, Stockholm, Sweden) located in the University of Health Sciences, Diskapi Yildirim Beyazit Training and Research Hospital, Department of Radiation Oncology. Three-dimensional water phantom system IBA Blue Phantom² (IBA Dosimetry; Schwarzenbruck, Germany) and IBA SP34 (IBA Dosimetry; Schwarzenbruck, Germany) model water solid phantom were used for the experimental measurements. The water phantom used in this study operates with OmniPro Accept v7 software (IBA Dosimetry. Schwarzenbruck. Germany).

All the measurements were conducted at 6 and 18 MV photon energies with a field size of 10×10 cm^2 and source-skin distance (SSD) of 100 cm. IBA Dose 1 (IBA Dosimetry; Schwarzenbruck, Germany) model electrometer and FC65P (IBA Dosimetry; Schwarzenbruck, Germany) model ion chamber were used for the solid water phantom measurements. The ion chambers and electrometer used were calibrated by the Turkish Atomic Energy Institute Secondary Standard Dosimetry Laboratory. Figures 1 and 2 show the water phantom (water) and RW3 used in the measurements, respectively.

The quality beam is determined as the tissue-phantom ratio ($TPR_{20/10}$) given in the following equation (1) [26].

$$TPR_{20/10} = 1.2661 \times PDD_{20,10} - 0.0595 \quad (1)$$

Where $PDD_{20/10}$ is the ratio of the percentage depth dose values at 10 and 20 cm depth for a field size of 10 × 10 ,cm^{-2}. and defined at the phantom surface with an SSD of 100 cm.

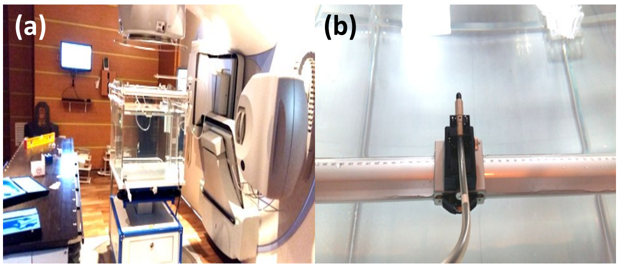

Figure 1. (a) Water phantom and experimental setup used for the measurements **(b)** Ion chamber.

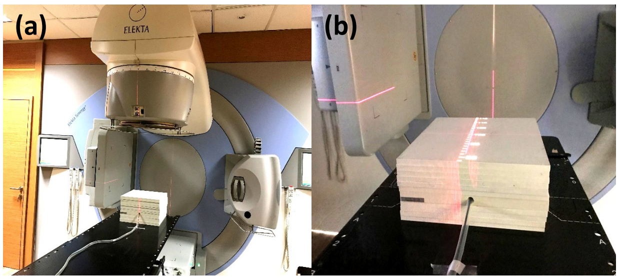

Figure 2. (a) Experimental setup for RW3; **(b)** RW3.

GEANT4/GATE simulations

The commercial materials with different densities used in this study were simulated using GATE 8.1 simulation program. The elemental features of the materials used in the simulation are given in table 1. The intensities, elemental compounds and atom numbers of the materials specified in the IAEA TRS-398 report were defined in the material list in the GATE simulation program [27-29]. Similar to the experimental setup, the phantom materials were simulated for a 10 × 10 cm^2. field size at SSD 100 cm using 6 and 18 MV photon energies. The phantom materials used were divided into voxels 30×30×30 cm^3 in size and the size of each voxel was determined as 20×20×5 mm^3. The energy spectrums for the photon beams of 6 and 18 MV spectrums were taken from the system database of the linear accelerator (Elekta Synergy) and defined in the simulation code. The number of histories for all simulations was 3×10^8.

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As seen in table 2, the difference between the mean dose values measured experimentally with the water phantom and the values obtained from the GATE program is <3% for 6 and 18 photon energies, except for PMMA material at 6 MV. The average dose difference between water phantom and RW3 for 6 and 18 MV photon energies is <1.5%. The $TPR_{20/10}$ values and average dose differences were calculated using equations (1) and (2), respectively. The $TPR_{20/10}$ values of water phantom and RW3, and the percentage dose differences are presented in table 3. The percentage dose differences of the simulated materials compared to water are also shown in table 4 for 6 and 18 MV photon energies.

Figure 3 shows the PDD curves obtained experimentally using water phantom and RW3 solid phantom at the field size of 10 × 10 cm^2. at 6 and 18 MV photon energies. Figures 4 and 5 show the PDD curves of the phantom materials defined in the simulation program and the measurement results carried out with the water phantom. Tables 5 and 6 present the percentage dose differences of the values obtained as a result of the measurement and simulation at various depths at 6 and 18 MV photon energies.

Table 1. Densities (ρ) elemental composition (fraction by weight) and average atomic numbers ($\bar{Z}$) of phantom materials used in the simulation.

	WT1 (27, 28)	RMI457 (30)	Plastic water (30)	Virtual water (30)	PMMA(31)	Polystyrene (31)	A150 (32)
H	0.0810	0.0809	0.0925	0.0770	0.0885	0.0774	0.1013
C	0.6720	0.6722	0.6282	0.6874	0.5998	0.9226	0.7755
N	0.0240	0.0240	0.0100	0.0227			0.0351
O	0.1990	0.1984	0.1794	0.1886	0.3196		0.0523
F							0.0174
Cl	0.00010	0.0013	0.0096	0.0013			
Ca	0.0230	0.0232	0.0795	0.0231			0.0184
Br			0.0003				
ρ (g/cm^3)	1.020	1.030	0.0003	1.030	1.190	1.060	1.127
Ź	5.95	5.96	6.62	5.97	5.85	5.29	5.49

Table 2. The average dose differences between the simulated phantom materials and experimentally measured water and RW3 results.

	6 MV - 10 x 10 cm^2			18 MV - 10 x 10 cm^2		
	Average (%)	**SD**	**p value**	**Average (%)**	**SD**	**p value**
Water vs RW3	-0.50	0.28	0.418	1.23	1.27	> 0.001
Water vs PMMA	3.66	1.43	0.031	-0.08	1.39	0.102
Water vs WT1	0.13	1.11	0.276	-2.80	2.17	0.126
Water vs RMI457	-0.29	0.91	0.628	-1.73	1.88	0.001
Water vs Plastic Water	0.92	1.14	0.002	-2.04	2.13	0.481
Water vs Virtual Water	-1.93	1.61	> 0.001	-1.65	2.10	0.754
Water vs Polystyrene	0.66	1.04	0.005	-1.64	1.94	0.178
Water vs A150	2.40	2.20	0.002	-1.08	1.53	> 0.001

Table 3. The experimental results of $TPR_{20/10}$ values of water phantom and RW3 solid phantom, and the percentage dose differences.

Energy	Water phantom	RW3	Percentage difference (%)
6MV	0.668	0.667	0.15
18 MV	0.767	0.757	1.31

Table 4. $TPR_{20/10}$ values of water phantom and the simulated materials and the percentage dose differences, at 6 and 18 MV photon energies.

	$TPR_{20/10}$							
Energy	**Water**	**PMMA**	**WT1**	**RMI457**	**Plastic Water**	**Virtual Water**	**Polystyrene**	**A150**
6 MV	0.668	0.639	0.684	0.691	0.681	0.689	0.678	0.653
18 MV	0.767	0.744	0.776	0.768	0.775	0.787	0.757	0.744
Per. Diff. for 6MV (%)		4.44	2.37	3.38	1.93	3.10	1.49	2.27
Per. Diff for 18MV (%)		3.04	1.17	0.13	1.04	2.57	1.31	3.04

Table 5. The percentage dose differences at 6 MV photon energy between the materials defined in the GATE simulation program and the measurements obtained from the water phantom.

PDD (%) – 6 MV – 10 x 10 cm^2												
Depth (cm)	1			5			10			15		
Material	**Meas.**	**GATE**	**Diff. (%)**	**Meas.**	**GATE**	**Diff. (%)**	**Meas.**	**GATE**	**Diff. (%)**	**Meas.**	**GATE**	**Diff. (%)**
Water vs PMMA	0.972	0.954	1.87	0.886	0.854	3.68	0.688	0.638	7.54	0.525	0.480	8.96
Water vs WT1	0.972	0.900	3.35	0.886	0.874	1.36	0.688	0.685	0.44	0.525	0.531	1.14
Water vs RMI457	0.972	0.943	3.03	0.886	0.885	0.11	0.688	0.691	0.44	0.525	0.525	0
Water vs Plastic Water	0.972	0.923	5.17	0.886	0.874	1.36	0.688	0.671	2.50	0.525	0.523	0.38
Water vs Virtual Water	0.972	0.920	5.50	0.886	0.879	0.79	0.688	0.668	2.95	0.525	0.521	0.76
Water vs Polystyrene	0.972	0.930	4.42	0.886	0.887	0.11	0.688	0.682	0.88	0.525	0.519	1.15
Water vs A150	0.972	0.941	3.24	0.886	0.878	0.91	0.688	0.661	4.00	0.525	0.508	3.29

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Table 6. The percentage dose differences at 18 MV photon energy between the materials defined in the GATE simulation program and the measurements obtained from the water phantom.

PDD (%) – 18 MV – 10 x 10 cm²												
Depth (cm)	3			7			10			15		
Material	**Meas.**	**GATE**	**Diff. (%)**	**Meas.**	**GATE**	**Diff. (%)**	**Meas.**	**GATE**	**Diff. (%)**	**Meas.**	**GATE**	**Diff. (%)**
Water vs PMMA	1.000	0.994	0.60	0.883	0.904	2.35	0.783	0.777	0.77	0.634	0.636	0.31
Water vs WT1	1.000	0.995	0.50	0.883	0.931	5.29	0.783	0.816	4.13	0.634	0.666	4.92
Water vs RMI457	1.000	0.992	0.80	0.883	0.919	4.00	0.783	0.807	3.02	0.634	0.656	3.41
Water vs Plastic Water	1.000	0.990	1.01	0.883	0.924	4.54	0.783	0.805	2.77	0.634	0.654	3.11
Water vs Virtual Water	1.000	0.989	1.11	0.883	0.906	2.57	0.783	0.807	3.02	0.634	0.659	3.87
Water vs Polystyrene	1.000	0.993	0.70	0.883	0.914	3.45	0.783	0.809	3.27	0.634	0.655	3.26
Water vs A150	1.000	0.990	1.01	0.883	0.915	3.56	0.783	0.794	1.40	0.634	0.647	2.03

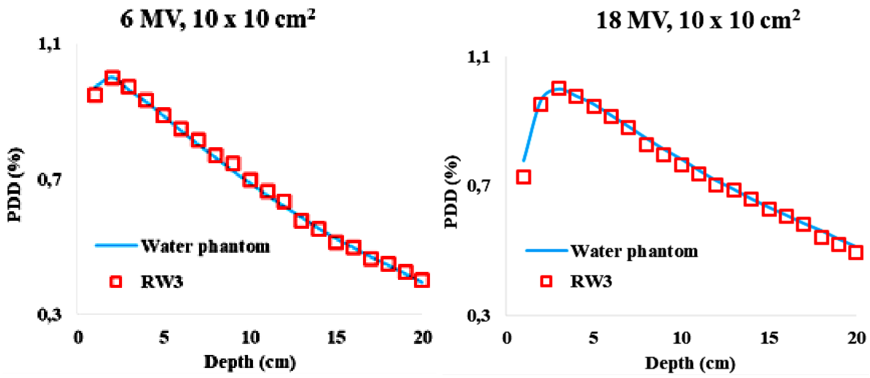

Figure 3. (a) Comparison of PDD values obtained using water phantom and RW3 at 6 MV and field size **(b)** Water phantom and RW3 at 18 MV and field size.

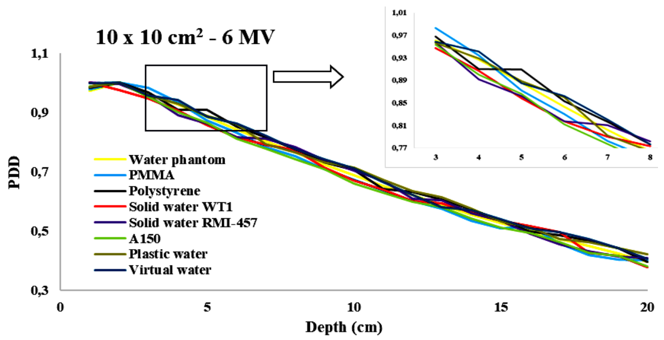

Figure 4. PDD values at 6 MV photon energy for the phantom materials obtained with GATE program and measured experimentally using the water phantom and 10 × 10 cm² field size.

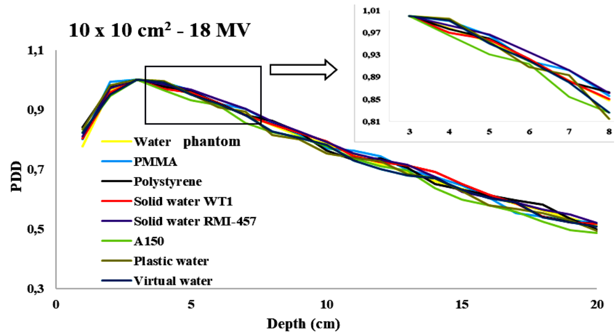

Figure 5. PDD values at 18 MV photon energy for the phantom materials obtained with GATE program and measured experimentally using water phantom and 10 × 10 cm² field size.

DISCUSSION

Tuğrul and Eroğul [(31)] obtained PDD results for PMMA, polystyrene, blood fluid, soft tissue and water phantom at 6 MV photon energy and field size of 10×10 cm² using the Monte Carlo-based BEAMnrc and DoseXYZnrc programs. It was stated that the intensity of the material was important for high energy photons and it was recommended that PMMA material should not be used instead of water phantom for dose control. In the current study, similar results were determined for PMMA at 6 MV photon energy and it was seen that the average dose difference of PMMA was higher than for other materials. The average dose difference between the water phantom and PMMA material was 3.66% at 6 MV, as shown in table 2.

Cameron *et al.* [(35)] simulated the various phantom materials to be used for dosimetry in microbeam radiotherapy and compared them with calculations performed with water. The results of that study determined that the closest phantom materials equivalent to water are Solid Water RMI457, Plastic Water DT, PAGAT and Virtual Water, respectively. In the current study, the closest materials equivalent to water for 6 MV photon energy were seen to be WT1, RMI457, Polystyrene, Plastic Water, Virtual Water, A150 and PMMA, respectively. At 18 MV photon energy, the closest materials equivalent to water were found to be A150, PMMA, Polystyrene, Virtual Water, RMI457, Plastic Water and WT1, respectively.

Hong *et al.* [(13)] investigated the differences between the PDD measurements made with water phantom and solid water phantom at 6/15 MV photon energies at the field size of 10 × 10 cm² at SAD 100 cm. It was stated that direct dose evaluation can

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be made with solid water phantom and that solid water phantom is practical as water phantom requires a long time for installation and has lower rate of repeatability. The values obtained with water phantom and RW3 were also seen to be compatible with each other in this study. The average dose difference between the water phantom and RW3 was <1.5% (table 2) and the difference between $TPR_{20/10}$ values for 6 and 18 MV photon energies was found to be 0.15% and 1.31%, respectively (table 3). Tekin *et al.* [36] studied the water equivalences of some solid phantoms using the Monte Carlo N-Particle Transport Code System-eXtendend (MCNPX) simulation program at different energies (59.5, 80.9, 140.5, 356.5, 661.6, 1173.2 and 1332.5 keV). Solid Water RMI457 and RW3 phantom materials were seen to have similar properties to those of water and can be used as radiation dosimetry at these energies. In the current study, the experimentally measured average dose difference of RW3 at photon energies of 6 and 18 MV was (-0.50±0.28)% and (1.23 ±1.27)% compared to water (table 2).

This result showed that RW3 can be used for dosimetry purposes at high energies as well as at low energies. The average dose differences obtained for RMI457 at 6 and 18 MV photon energies using GATE simulation were found to be (0.29 ±0.91)% and (-1.73±1.88)%, respectively (table 2). It was also determined that RMI457 phantom material has better results at 6 MV photon energy. Diteko *et al.* [37] obtained the PDD and $TPR_{20/10}$ values of the phantom material and Solid Water RMI457 using IBA Blue phantom² water tank at 6 MV, 8 MV, and 18 MV photon energies. At 6 MV photon energy, the PDD percentage differences between Solid Water RMI457 and water were found to be -3.9%, 0.6%, 0.6% and 0.4 at 1, 5, 10 and 15 cm, respectively. At 18 MV photon energy, the PDD percentage differences were obtained as -0.1%. 0.2% and 0.0% at 3, 10 and 15 cm, respectively.

In the current study, the percentage differences in PDD at 6 MV photon energy at depths of 1, 5, 10 and 15 cm were found to be 3.03%. 0.11%. 0.44% and 0.00%, respectively (table 5). At 18 MV photon energy, these differences were 0.8%. 3.02% and 3.41% at 3, 10 and 15 cm depths, respectively (table 6). Diteko *et al.* [37] reported $TPR_{20/10}$ percentage differences between Solid Water RMI457 and water to be -1.3% and -0.8%, respectively for 6 and 18 MV photon energies. In the current study, the $TPR_{20/10}$ percentage differences for 6 and 18 MV photon energies were determined to be 3.38% and 0.13%, respectively (table 4).

Aslam *et al.* [38] used BEAMnrc and DOSXYZnrc codes for phantom dose measurements by simulating the head of LINAC device. The soft tissue equivalence of water, PMMA and polystyrene were investigated at 6/10 MV photon energy and 5 × 5 cm^2 and 10 × 10 cm^2 area sizes. The closest equivalents to soft tissue were found to be water, PMMA and polystyrene, respectively. In that study, polystyrene was seen to have closer equivalence to water than PMMA. The average dose difference between the PDDs of the water phantom and polystyrene material at 6 MV was (0.66 ± 1.04)%, while it was (3.66 ± 1.43)% with PMMA. Araki *et al.* [39] studied the dosimetric properties of solid water 557 (SW557) and solid water 457 (SW457) phantoms using 4, 6, 10, and 15 MV photon energies with the field size of 10x10 cm^2. It was stated that SW557, which has almost the same density value as water, displayed better dosimetric properties than SW457 and was a more suitable material for water equivalent. Similarly in the current study experiments, the values obtained from measurements made with RW3 and water phantom were seen to have good agreement with each other.

CONCLUSIONS

All the materials examined in this study were found to be suitable for usage for daily dosimetric measurements. WT1 and RMI457 has the closest equivalence to water phantom at 6 MV photon energy, while PMMA and A150 are suitable choices at 18 MV photon energy. Using a water phantom rather than a solid water phantom will minimize measurement uncertainties. The most accurate choice would be to use water phantom for each dosimetric measurement in radiotherapy clinics based on the possibilities and time.

Ethical consideration: Research does not involve human participants or animals Informed consent: none.

Conflict of Interest: There is no conflict of interest in this study.

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Author's contributions: All authors approved the latest version of the article. In this study, the contributions of the authors are equal.

REFERENCES

1. International Atomic Energy Agency (2000) Absorbed dose determination in external beam radiotherapy: an international code of practice for dosimetry based on standards of absorbed dose to water. IAEA Technical Reports Series. No. 398.
2. Podgorsak EB (2005) Radiation Oncology Physics: A handbook for teachers and students. International Atomic Energy Agency. Vienna. Austria
3. Almond PR, Biggs PJ, Coursey BM, Hanson WF, Hug MS, Nath R, Rogers DW (1999) AAPM's TG-51 protocol for clinical reference dosimetry of high energy photon and electron beams. *Medical Physics, **26**(9): 1847–1870*.
4. Ramaseshan R, Kohli K, Cao F, Heaton R (2008) Dosimetric evaluation of plastic water diagnostic therapy. *Journal of Applıed Clinical Medical Physics*, *9(2): 98-111*.
5. Zuber SH, Yusof MFM, Hashikin NAA, Samson DO, Aziz MZA, Hashim (2021) A Rhizophora spp. as potential phantom material in medical physics applications-A review. *Radiation Physics and*

[DOI: 10.52547/ijrr.20.3.27]

Chemistry, *189*.
6. Ramos SMO, Thomas S, Berdeguez MBT, Sa LV, Souza SAL (2017) Anthropomorphic phantoms-potential for more studies and training in radiology. *Int J Radiol Radiat Ther, **2**(4): 1-5*.
7. American Association of Physicists in Medicine (AAPM) (1983) A protocol for the determination of absorbed dose from high-energy photon and electron beams. Task Group 21. *Medical Physics*, ***10** (6): 741–771*.
8. Samson DO, Jafri MZM, Shukri A, Hashim R, Sulaiman O, Aziz MZA, Yusof FM (2020) Measurement of radiation attenuation parameters of modified defatted soy flour–soy protein isolate-based mangrove wood particleboards to be used for CT phantom production. *Radiat Environ Biophys, **59**: 483–501*.
9. Dohm OS, Christ G, Nüsslin F, Schüle E, Bruggmoser G (2001) Electron dosimetry based on the absorbed dose to water concept: A comparison of the AAPM TG-51 and DIN 6800-2 protocols. *Medical Physics*, ***28**(64): 2258–64*.
10. Huq MS and Andreo P (2001) Reference dosimetry in clinical high-energy photon beams: Comparison of the AAPM TG-51 and AAPM TG-21 dosimetry protocols. *Medical Physics*, ***28**(1): 46–54*.
11. Hill RF, Brown S, Baldock C (2008) Evaluation of the water equivalence of solid phantoms using gamma ray transmission measurements. *Radiation Measurements*, ***43**(7): 1258-64*.
12. Seuntjens J. Olivares M. Evans M. Podgorsak E (2005) Absorbed dose to water reference dosimetry using solid phantoms in the context of absorbed-dose protocols. *Medical Physics*, ***32**(9): 2945-33*.
13. Hong JW, Lee HK, Cho JH (2015) Comparison of the photon charge between water and solid phantom depending on depth. *Int J Radiat Res, **13**(3): 229-234*.
14. Gargetta MA, Briggsa AR, Bootha JT (2020) Water equivalence of a solid phantom material for radiation dosimetry applications. *Physics and Imaging in Radiation Oncology*, ***14**: 43–47*.
15. Hill R, Holloway L, Baldock CA (2005) Dosimetric evaluation of water equivalent phantoms for kilovoltage X-ray beams. *Physics in Medicine and Biology*, ***50**(21): 331–344*.
16. White DR, Speller RD, Taylor PM (1981) Evaluating performance characteristics in computerized tomography. *The British J Radiology*, **54**(639): 221–231.
17. Allahverdi M, Nisbet A, Thwaites DI (1999) An evaluation of epoxy resin phantom materials for megavoltage photon dosimetry. *Physics in Medicine and Biology*, ***44**(5): 1125–32*.
18. Saitoh H, Myojoyama A, Tomaru T, Fukuda K, Fujisaki T, Abe S (2002) A study on properties of water substitute solid phantom using EGS code. Proceedings of the Tenth EGS4 Users Meeting in Japan. *KEK Proceedings*, ***18**: 55-64*.
19. Tello VM, Tailor RC, Hanson WF (1995) How water equivalent are water-equivalent solid materials for output calibration of photon and electron beams? *Medical Physics*, ***22**(7): 1177-89*.
20. Nilsson B, Montelius A, Andreo P, Johansson J (1997) Correction factors for parallel-plate chambers used in plastic phantoms in electron dosimetry. *Physics in Medicine and Biology, **42**(11): 2101-18*.
21. Hill RF, Kuncic Z, Baldock C (2010) The water equivalence of solid phantoms for low energy photon beams. *Medical Physics, **37**(8): 4355–63*.
22. Samson DO, Shukri A, Jafri MZM, Hashim R, Aziz MZA, Yusof MFM (2021) Development of radiation dosimetric phantoms made from SPC/NaOH/IA-PAE/Rhizophora spp. particleboards. *Int J Radiat Res, **19**(4): 801-811*.
23. Vahabi SM, Bahreinipour M, Zafarghandi MS (2017) Determining the mass attenuation coefficients for some polymers using MCNP code: A comparison study. *Vacuum, **136**: 73–76*.
24. Kumer T, Kumar Das P, Khatun R, Rahman A, Akter S, Kumar Roy S (2021) Comparative Studies of Absolute Dose in Water Phantom. Solid Water Phantom and MatriXX with MULTICube Phantom. *International Journal of Medical Physics. Clinic Engin and Radiat Oncol*, ***10**: 169-17*.
25. Ababneh B, Tajuddin AA, Hashim R, Shuaib IL (2016) Investigation of mass attenuation coefficient of almond gum bonded Rhizophora spp. particleboard as equivalent human tissue using XRF technique in the 16.6-25.3 keV photon energy. *Australas Phys Eng Sci Med*, ***39**(4): 871-876*.
26. Followill DS, Tailor RC, Tello VM, Hanson WF (1998) An empirical relationship for determining photon beam quality in TG-21 from a ratio of percent depth doses. *Medical Physics*, ***25**: 1202–05*.
27. International Commission on Radiation Units and Measurements (1984) Stopping Powers for Electrons and Positrons ICRU Report 37.
28. International Commission on Radiation Units and Measurements (1989) Tissue Substitutes in Radiation Dosimetry and Measurement. ICRU Report 44.
29. International Atomic Energy Agency (1997) The Use of Plane-parallel Ionization Chambers in High-energy Electron and Photon Beams. An International Code of Practice for Dosimetry. IAEA Technical Reports Series No. 381.
30. Borcia C and Mihailescu D (2007) Are water-equivalent materials used in electron beams dosimetry really water equivalent? *Rom J Phys, **53**(7-8): 851–863*.
31. Tuğrul T and Eroğul O (2019) Analysis of water-equivalent materials used during irradiation in the clinic with XCOM and BEAMnrc. *J Radiat Res and Appli Sci, **12**(1): 455-459*.
32. https://physics.nist.gov/cgi-bin/Star/compos.pl?matno=099.
33. Duran-Nava OE, Torres-Garcia ER, Oros-Pantoja R, Hernandez-Oviedo JO (2019) Monte Carlo simulation and experimental evaluation of dose distributions produced by a 6 MV medical linear accelerator. *Journal of Physics Conference Series*. 1221.
34. Sahmaran T and Kaskas A (2020) The effect of the trace elements concentrations on the cancerous and healthy tissues in radiotherapy. *International Journal of Medical Physics. Clinic Engine and Radiat Oncol*, ***9**: 110-124*.
35. Cameron M, Cornelius I, Cutajar DL, Davis JA, Rosenfeld AB (2017) Comparison of phantom materials for use in quality assurance of microbeam radiation therapy. *J Synchrotron Rad, **24**: 1-11*.
36. Tekın HO, Sayyed MI, Erguzel TT, Karahan M, Kılıcoglu O, Mesbahı A, Kara U (2018) Investigation of water equivalance and shieldıng properties of different solid phantoms using mcnpx code. *Digest J Nanomaterials and Biostructures, **13**(2): 551-62*.
37. Diteko K, Mkhize TD, Mohlapholi MS (2020) Validating the percentage depth doses using two different phantom materials. *Insights Med Phys, **5**: 1-7*.
38. Aslam A, Kakakhel MB, Shahid SA, Younas L, Zareen S (2016) Soft tissue and water substitutes for megavoltage photon beams: An EGSnrc-based evaluation. *J Applied Clinical Medical Physics, **17**(1): 408-15*.
39. Araki F (2017) Dosimetric properties of a solid water high equivalency (SW557) phantom for megavoltage photon beams. *Physica Medica*, ***39**: 132–136*.

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